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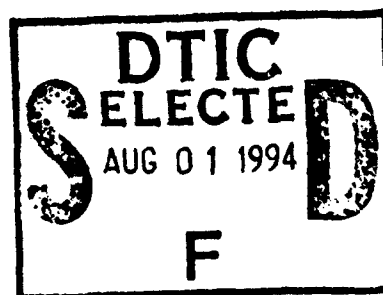
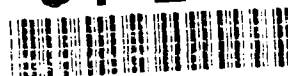# STUDY OF ADVANCED ELECTRONIC APPLICATIONS TO AERONAUTICAL DISPLAY AND CONTROL PROBLEMS

by G. B. Litchford

94-21958

Prepared by
LITCHFORD SYSTEMS
Northport, N. Y.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1969

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I. INTRODUCTION

A. SUMMARY OF ELECTRONIC APPLICATIONS TO THE FIELD OF AERONAUTICS

The very rapid growth of aviation, particularly the civil applications of the airplane to the transport of cargo and people, has already created many problems. The growth projections for general aviation indicate that as many as 150,000 such aircraft for business, air taxi, and pleasure will soon be flying. The upgrading of both the pilot skills and the complexity of the aircraft are often made possible by the extensive applications of electronics. Although their growth is not reflected directly in the numbers or percentages of actual airframes, the air carriers still serve vastly increasing numbers of the traveling public, since the capacity of each aircraft is increasing. The Boeing 747, the Douglas DC-10, and the Lockheed 1011 with potential capacities of nearly 500, 300, and 300 people respectively will carry as many passengers as 20 to 25 aircraft did in the early days of the industry. The enormous potential loss of life and property in a single accident would, therefore, be a national tragedy.

The total air traffic problems generated by the projected growth of the two segments of aviation, when combined with the military segment, will become enormous. The potential airspace conflicts increase geometrically with the number of simultaneous users of the airspace. Thus, the problems of collision rise rapidly, and the likelihood of air traffic delays is already evident to such an extent that the total time of many operations during busy hours is almost double the actual air time. Although the number of military and airline aircraft are not increasing at the rate of general aviation, their speeds and frequency of service (or missions per aircraft) are increasing. The concept of "see and be seen"--that is, the visual flight rules--is already severely stretched. The increase in air traffic and the increase in the traffic's speed has made visual avoidance of other aircraft a doubtful matter in many high density

areas. By 1975 this problem will be much more aggravated, and some form of air-to-air and/or air-ground electronic developments will be absolutely essential for safe flight. The current electronic systems will probably be retained for some years, but their capacities will not match the increased demands; thus, supplemental or even entirely new concepts of electronic aids for safe traffic movements of all types of aircraft will eventually be needed.

The size, cost, and economics of airline operations permit the absorption of the costs for the required electronics equipment. It is estimated that a single aircraft, such as one of the jumbo jets or an SST, will carry about one million dollars worth of electronic equipment. General aviation aircraft cannot follow suit, yet means must be found for the safe sharing and efficient assignment of the airspace used by these aircraft under both IFR and VFR conditions. An air taxi operator, for example, is just as anxious to operate in high density or IFR conditions as the airlines, since the demand for carrying passengers to or from airports is at a peak under these conditions. The business jet operating under similar conditions is just as important to the owner, since he justifies the aircraft for economies of corporate operation. Restrictions on operations greatly reduce this corporate value.

Many users, particularly the airlines, are intent on operating in very low visibility weather (CAT II and III). Normal en-route airways flight under these conditions is safe because of the lower densities. However, the terminal areas require extensive additional electronics, such as multiple receivers for VOR, localizers, glide paths, markers, homing beacons, secondary surveillance radars (SSR), transponders, identification coding signals, etc. Distance measuring equipment (DME) is also being used more and more. These aids expedite traffic, but those aircraft that do not have them aboard will often be delayed. A very-low-cost general aviation beacon with minimum coding will aid, since the extensive and costly ATC system of the FAA is being oriented about the SSR system.

identity, position, and altitude are all being transmitted from
the aircraft in digital format for ground processing and display.
This system is a great improvement over the visual "skin return"
radars of the past. The basic primary radar problems of ground
clutter, lack of identity and altitude, MTI blind-speed, miniscule
signal returns from small targets (competing with rain, clutter,
or other weather returns) are all eliminated by the new secondary
radar and cooperative airborne transponder.

Based on this general background, the application of
electronics to some of these problems has been studied and evaluated.
The ability of an aircraft to maintain a stable flight path is
a great aid in complying with ATC instructions (radio switching,
instrument reading, etc.) and for low visibility approaches.
Because of their flight characteristics, some aircraft in the general
aviation field require continuous activation of the controls to
retain a stable flight path—upsets due to turbulence, aircraft (jet)
wakes, etc., are problems. The use of electronics by the human
requires the outputs to be in a form to which his sensory system
can respond. The indication of a radio·path in space by a zero-
centered (crossed-pointer) meter movement is quite prevalent. This
basic concept is used in many forms for VOR, DME, glide slope, and
localizer guidance. Radio propagation faults such as lobing, multi-
path, scalloping, and signal dropouts must be considered in the use of
any pilot display. Optimizing flight control and radio guidance in
concert is essential for maximum effectiveness. Consideration must
also be given to more graphic displays for curved flight paths such
as the "round-out" of steep approaches for noise abatement or VSTOL
landing. Aural signals were used in the past more than today and
may offer some alleviation of the human's "visual workload" when
e is dependent on electronic flight aids. Certainly, warnings,
and even complementary (double checking) guidance signals, might
e provided aurally to the pilot. Annunciator, or "cuing," lights
warning of an imminent situation need study. Lower altitude limits,
ow and high speed limits, flare or visual contact limits, etc.,

to the pilot might be established with such lights or aural signals. The nature of the radio navigation signals, modulation, duty cycle, data formats have large effects on pilot displays and flight controls; consequently, they must be examined first.

The decreased cost, reliability, and ease of air travel makes it the most desirable means of transportation. Many other forms of rapid transportation have been reduced in service to such an extent that many travelers are today completely dependent on the airplane. This increased dependence requires a full assurance that the aircraft can land in adverse weather at its destination. Otherwise, the nation'a major transport system is limited and hazards exist without a fully engineered and operationally proven low-visibility capability. The field of low-visibility landing is emerging as one of aviation's basic barriers, just as the sonic barrier was once recognized (and then resolved). Part of the solution evidently relates to the interdisciplinary aspects of piloting, visual cues, measurements of visibility, radio guidance, aircraft handling properties, and cockpit displays. Although each of these areas has its own "island" of know-how and technology, there is little organized effort to develop interrelationships between these specialties, which are often technically diverse. An assessment of the "total-system" is needed.

The field of electronic simulation offers the possibility of establishing some of these interrelationships, so that communication channels between the aeronautical, electronic, display, human factor, and visual aid specialists can be established. No common language or understanding exists today on a sufficient basis for resolving this major, national, civil-military problem. For example, the effect of a radio altimeter measuring height (above the immediate approach terrain) on the display of the landing point (some several thousand feet ahead and at a different elevation) has not been simulated for the existing approach profiles of some of the major airports. The use of displays that permit easy and safe transition

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a visual landing for CAT II, IIIA, and IIIB is the most difficult
to simulate. Radio errors in height and centerline alignment near
the threshold can place the pilot in a frame of mind in which he
expects to see something different than what actually becomes
visible at 100 feet of height or less (with about 8 to 10 seconds
to go). This discrepancy between the mental picture created by
the guidance display of the offset beams (yet within tolerances)
and the actual visual cues, can be tolerated only within certain
limits. What are the limits? Can the aircraft be maneuvered onto
centerline with correct heading and touchdown point in the few
seconds remaining? These fine details for CAT IIIA and IIIB must
be simulated in a far more realistic manner than has been achieved
up to now. Even actual flight in artificially created low visibility
conditions (smoke) below 200 feet is a possibility, so that the
electronic simulation can be checked and made to correlate with
the "real" (very-low visibility) world. Computer-graphics, real
time displays, computer-generated films, each electronically-
generated from a computer with data storage of the landing scene,
is a promising technique worthy of exploitation.

. ELECTRONIC PROBLEMS ENCOUNTERED IN GENERAL AVIATION

As noted in paragraph A of this section, the extensive
growth and increasing sophistication of General Aviation requires
the planning of electronic aids for navigation, ATC, collision
avoidance, etc., so that the pilot with minimum IFR capability
is accommodated. This increase will undoubtedly call for greater
skill in all these areas that could be greatly assisted by electronics.
low-cost units and concepts must be considered, since current
airline and military systems (inertial, DME, SSR, CAT III landing,
etc.) are often out of the financial reach of most in the General
Aviation group. Such concepts as the simple use of communications
equipment for positioning (greater implementation of VHF-DF into
sets), and "time-of-arrival" from an FSK-VHF communications signal

should be considered. A simple FSK crystal might suffice with a controlled transmission time and period; the total electronic equipment costing perhaps $100 when produced in large quantities. Use of time-shared VOR signals, Omega, multi-tone data signaling, and tone DME, are techniques that are compatible with the next decade of ATC-Nav facilities yet may provide large rewards at low cost to the average General Aviation group.

The ATC (SSR) beacon transponder system is now in wide use and is a major adjunct to the Military, FAA, and ICAO electronic complexes for safe ATC. However, the lowest-cost units are still in the one to two thousand dollar region (installed). With electronic technology developing so quickly, a solid-state, stable unit (with perhaps only bracket--20.3 microsecond--pulses) should be considered if it could be realized for, say, under $300. The vast numbers of General Aviation aircraft could then afford to acquire and use such a unit.

The influence of such a unit on the ground system should also be considered, since so many additional transmissions could overload the system. Some possibility of opening an adjacent channel for General Aviation reply, cross-band reply on another frequency, with reduced tolerances of DME pulse formats is examined. The processing of the emissions from the low-cost airborne units might require some minimum additions to ground processing. Yet General Aviation outputs could be fed directly into the same displays as the remainder of the SSR system. Ground equipment to effectively eliminate interference is in development and use.

VORTAC, which includes the costly DME units, may be surplanted in time with a low-frequency system for General Aviation such as Omega. Of all the low-frequency systems--Decca, Loran A, C, D, Consol, etc.--Omega has certain potentials that should be studied. An evaluation of its application to General Aviation is made in this report. Its simplicity and probable low cost for small area coverage using "differential" techniques has not been thoroughly

examined to date. The utilization of electronic guidance signals for General Aviation displays and flight path control is also broadly evaluated in this report. Potential "Area Systems" such as Omega might be presented to the pilot with simplified displays that are not now common. A simplified "Tone-DME" on the VHF communications channels was tested a few years ago and will be reviewed; it offers a very-low cost method compared with the L-band techniques of the current VORTAC/DME. Consolidation of L-band DME and SSR is also possible to reduce cost. DME and SSR applicable to shorter ranges and decreased accuracy may often suffice for General Aviation and permit cost reductions.

The practical approach has been taken of examining existing functions and electronic facilities both air and ground (since many of them are cooperative systems). This has been done to determine whether more information, more utility, and lower-cost service can be extracted for the General Aviation pilot (typified by the single-engine four-place or less aircraft). Whatever degradation (if any) may occur is examined to assure that there is no degradation to other users (such as airlines) and that the results are commensurate with this portion of General Aviation. The overall situation now requires some major low-cost improvements. Proposed practical solutions for low-cost improvements for low-cost General Aviation aircraft are long overdue. The welfare of this sector of aviation and the safe public use of air carrier services is involved.

This is considered the most realistic approach during the 1970-1980 decade, since single-engine aircraft are projected as composing over 80% of the General Aviation aircraft population even by 1976. This critical approach also permits the more costly single-engine (over four-place) and the multi-engine General Aviation aircraft to be included. It specifically is aimed at bringing into the national ATC and IFR planning the portion of the General Aviation community that is most difficult to aid with

current aviation electronics because of the high cost of equipment manufacture and implementation. Facilities and equipment for air carrier aircraft are normally more costly than those for General Aviation aircraft.* This service is more demanding because of the widely differing flight characteristics of speed, maneuverability, runway requirements, approach angles, cruise altitudes, etc.

Only a small percentage of the nation's three thousand paved and lighted airports have an instrument approach capability or any form of IFR traffic regulation that would be technologically and economically commensurate with the current and projected population mix of General Aviation aircraft.

An SSR low-powered interrogator and tower display could be added during 1970-1980 to hundreds of the 3000 airports (whose surrounding area is the habitat of most General Aviation) at a cost of only about 25 thousand dollars per airport (vs 2 to 3 million dollars per airport for a full ARSR or ASR radar). An SSR system with solid coverage to 30 miles could readily be provided. Admittedly, "skin-track" or primary radar return is eliminated as is the usual 200-mile SSR service, but for a 30-mile service range, it would be a much appreciated function, permitting IFR and some low visibility approach operations in the vicinity of the field. The interlacing of any General Aviation activity with airline activity (many feeder lines and air-taxi services also use the same fields) is provided as is a useful approach facility for, say, a 300-foot ceiling and ¾-mile visibility for a slow, maneuverable, General Aviation aircraft (not suited for a high-speed, much less maneuverable, jet transport).

A greatly simplified proximity warning signal can be derived from the SSR signals. One possible method is outlined in

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* It is estimated there will be 100,000 aircraft priced at under $15,000 and 50,000 additional priced at under $30,000 in the 1975-1980 time period. Some 35,000 aircraft costing $30,000 to $75,000 are also candidates for low cost electronic equipment (total population 180,000).

this report that could further enhance the value of the low-cost transponder to the General Aviation pilot. Considerable testing of a "listen-in" feature on the airborne transponder of the SSR system is required to establish useful proximity ranges and to determine the value of such a function to collision avoidance. It is a very-low cost approach to the Proximity-Warning Indicator (PWI)-Collision Avoidance System (CAS) problem that is compatible with the rest of the ATC system. Thus, some form of collision avoidance (though limited could be implemented for the immediate future before a fully satisfactory (yet, estimated as costly) system is evolved and implemented.

II. APPLICATION OF ELECTRONICS FOR NAVIGATION AND DATA TRANSMISSION OF GENERAL AVIATION AIRCRAFT

A. GENERAL

General aviation has become such a broad term that it is now applied to over 100,000 aircraft ranging in cost from two million dollar jets to single-engine, private aircraft costing a few thousand dollars. It is important to define that portion of general aviation that we will be mostly concerned with--improved low-cost navigational services. We will examine in Section III Surveillance and ATC involving low cost transponders.

Types	Estimated Number (in thousands)		
	1967	1972	1977
Single-Engine Piston	90	120	145
Multi-Engine Piston	13	18	23
Turbine	1	4	8

It is obvious that if attention is to be given to low-cost navigational electronics, the large category of single-engine aircraft is the area that requires most attention. Equipments to improve the safety and usefulness of single-engine aircraft are more difficult to engineer for performance and cost in this category of aircraft. Yet, such efforts will provide the greatest benefit to the greatest population.

The categories of multi-engine and turbine-engine aircraft often are in a price class of 100,000 to 400,000 dollars, a cost region that warrants, say, a 10% investment in electronics. Such an amount will often provide a moderately good complement by today's standards for FAA-IFR flight in high-density air traffic areas. Such a complement might cost:

a.	Communication Receiver--VHF	$1,500
b.	Communication Transmitter--VHF	3,000
c.	Stability Augmentation	3,000
d.	Dual VOR (Localizer) Receiver	2,500
e.	Marker Beacon Receiver	500
f.	Glide Slope Receiver	1,500
g.	ADF	1,000
h.	DME	2,500
i.	SSR Transponder	2,500
j.	Displays and Installations of Antennas for Above	3,000
	TOTAL	$ 00

(Attitude and basic instruments are not included

Airline category equipments, dual installations, and modernized displays of these navigational signals can increase this 21,000 dollar figure by two or three times. In spite of this high figure, some basic elements are missing, such as CAT III landing, air-to-air signaling, and a data link. These and other elements may be essential by 1975 at present rates of aviation growth.

Thus, with the single-engine aircraft costing in the 6,000 to 30,000 dollar range (Flying Magazine's Annual Guide), averaging about 18,000 for the approximately 50 types now being sold in the United States, it is unlikely that the pilot or owner will be able to afford a 21,000 dollar electronics package. Attitude instruments such as directional gyro, magnetic gyrocompass, pitch and roll indicator, altimeter, etc., can add considerable cost and are essential with the radio and electronics for any realistic IFR flight. Probably the practical minimum for full IFR by today's standards may be in the 25,000 dollar range.

Many a general aviation pilot and/or owner will be denied IFR flight at these prices. Furthermore, the growing numbers of these aircraft can create hazards for themselves and others who have acquired the necessary equipments, unless they are constrained

by regulation to given airspace assignments, visibility conditions, and are possibly restricted from high density airspace. With the increase in speed of most airline aircraft and the increasing number of airports served by the regional airlines, the airspace consumed by the equipped aircraft is increasing. In due time, say one or two decades hence, much of this airspace will be denied the non-equipped or under-equipped aircraft.

The use of electronics in these single-engine aircraft is for navigation, communications, ATC, landing, proximity warning and collision avoidance. The possibility that the small aircraft (even under VFR) collides with a larger aircraft, an airliner, or another general aviation aircraft, increases yearly, since such probabilities increase at rates in excess of the linear rate--possibly by the squared cube.

It has often been assumed that mass production of certain items will further reduce the cost of the general aviation low-cost electronics. This may not be the case for two reasons. Normally, in electronic production, units manufactured by the millions, such as TV, radio, audio-hi-fi, etc., permit manufacturing techniques that are very effective in cost reduction. However, there are certain basic complexities in the existing VOR receiver, DME, the SSR beacon, and similar standardized units that make cost reduction difficult.

To illustrate, let us take the problem of the VOR receiver and assume the following: It must be carried on all aircraft and be capable of processing two 30-cps signals that must be isolated by about 60 db so that a phase measurement (electrical phase angle is also navigational phase angle) can be made. The receiver also requires dynamic signal ranges, sub-carriers, phase shifters, phase detectors, and DC analog readouts that are well beyond the normal engineering of a simple, home receiving equipment. Reliability must also be higher because of the more adverse environment. The probability of achieving a marked cost reduction for a given unit

with a production run of about 200,000 (general aviation) units over that now achieved with, say, 20,000 units is not very considerable. Furthermore, such a market is distributed among at least five manufacturers over a period of 5 to 10 years, so that an individual manufacturer cannot realize a true mass production approach as with other electronic products.

B. LOWERING COSTS BY "TOTAL-SYSTEM'S" APPROACH

One promising approach to the cost reduction problem is the examination of the total number of elements now required by current ATC and IFR criteria. The number of receivers, transmitters, data processing equipments, pilot readouts, power supplies, antennas, control heads, cabling, etc., that must be added to the aircraft itself is tremendous. Perhaps an airline 707 type aircraft can readily accept this and even greater costs, since a several million dollar airframe investment and a commensurate commercially rewarding utility is involved.

On this basis of comparing, as an example, a 6,000,000 dollar transport with a 20,000 dollar general aviation aircraft, there should be a 300 to 1 ratio in the benefits ratio of electronics to airframe costing.

C. RANDOM SYSTEM EVOLUTION

An examination of the history of ATC and navigation (with their related communication, landing, collision-avoidance, and other features) indicates that the system evolved slowly with one element of electronics being added every few years as needed. Integration of the ILS localizer with the VOR and communication equipment, so that a continuous band from 108 to 136 Mc is available for these three functions, was one of the few efforts at integration. This permitted sharing of the receiver local oscillator, power supply, frequency channelization, antenna, etc. Nevertheless, the communication signals were polarized vertically whereas the

navigational signals were polarized horizontally.

The glide slope signal, for reason of propagation, was forced higher in frequency to around 330 Mc. In the future it appears that a much higher frequency will be used for this purpose, because the choice has not been a very good one. To eliminate path variables, vertical glide path apertures of over 100 feet in height are needed. Similarly, the ATC beacon transponder was added; a most important element in the new FAA and International (ICAO) concepts of ground surveillance and control of airborne traffic. It operates near 1,000 Mc. This system is the outgrowth of the MK-X-IFF beacon. The DME is somewhat related because much of the technology was first adapted from the MK-X (and MK-V, World War II) programs. Even though both the DME and SSR use pulse transmission in the 1,000-Mc region, they are not integrated in any way; essentially duplicate airborne transmitters and receivers are used because no need existed at the time to simplify and economize. Even the pulse shapes and signal formats (channelization, codes, etc.) are non-compatible.

These are mostly equipments and concepts developed in the 1940's and early 50's and have provided excellent service. In spite of some now obvious limitations, they will continue to serve civil aviation for at least another decade, since little else is in the late stages of development. It is, however, evident now, in the late 1960's, that the 1970-1980 era will permit a far better total system synthesis of low-cost general aviation guidance electronics. System overloads and improved electronic technology will combine to emphasize the need for modern system integration planning and development.

D. FUNCTIONAL INTEGRATION OF ELECTRONICS FOR GENERAL AVIATION

A first requirement in the integration of electronics for general aviation should be a full examination of the needs of general aviation and the new technical approaches needed for the

1970-1990 period. The past piecemeal approach can be circumvented
with today's knowledge and experience, so that a minimum of elec-
tronic units in the form of transmitters, receivers, processing dis-
plays, etc., would be needed for the maximum of functions. This
would not only greatly reduce the overall price of the general
aviation units but assure an adequate number of new functions that
will be essential by the late 1970's if the growth of both airline
and general aviation flying continues along current projections.
Such an effort would also provide a means for representing those
sectors of general aviation that now have little voice, no research
engineering staffs, and no way to technically determine what they
need in the future. The joint efforts of engineers and administrators
will undoubtedly permit a successful evolution that will result in
the maximum use of the airspace by the electronically equipped,
low-cost aircraft, commensurate with the public interest and airline
usage of airspace.

The present trend is to force the small general aviation
aircraft to conform to the increasingly costly and technically com-
plex National Airspace System. The operational dominance in IFR
and ease of compliance with ATC by the airlines is still in the
public interest, since the public use of airlines far outnumbers
the public use of general aviation aircraft. However, the challenge
now is the need to protect the public when utilizing the airlines
and to provide greater safety and utility to the user of the medium-
and low-cost general aviation aircraft. It is predominantly a
technical challenge to determine whether a low-cost electronics pro-
gram can develop that is commensurate with the remainder of the
civil navigation, ATC, and communication environment.

E. LOW-COST ELECTRONIC AIR AND GROUND AIDS

Several systems, techniques, and concepts are outlined
here that typify the technical spectrum available today (for analysis,
eventual testing, and ultimate synthesis of a general aviation

electronics program). It must be recognized that at least a decade will elapse before any basically new navigation and guidance systems can be made available to general aviation. Thus, the immediate problem for the next decade is twofold. Advanced R & D for totally new systems suited to the 1980-1990 time frame must be underway simultaneously with projects to modernize and extract more useful data at lower costs from existing and fully committed systems. Both approaches are essential and both are very urgent.

It is probable that a partially integrated 1970-1980 program can be developed without so-called "breakthroughs," using basically shrewd system planning, flight validation, and modified system standards. Shrewd, as Webster's International explains, is: "A blended, practical, hard-headed, cleverness, judgment, and acute perception." Candidate systems, techniques, and concepts are listed to typify the extent of the available technology that could be applied in the next few years.

1. VHF Omnirange (VOR)
2. DME (L-band pulse system)
3. VOR-DME (combined for full area usage)
4. TACAN (L-band Omni and DME)
5. Marker Beacon (75-Mc pin-point check)
6. Localizer (runway, IFR guidance, VHF)
7. Glide Path (runway, vertical guidance, UHF)
8. Omega area navigation system (VLF)
9. Loran-C area navigation system (LF)
10. Satellite Navigation Systems
11. TONE-DME multiplexed on VHF communication or navigation services (one-way and two-way)
12. FSK or pulse time-of-arrival location system
13. Ground-based, Doppler-DF for VHF communications
14. Very-low-cost SSR-ATC transponder
15. Omega "phase-scanning" for ATC and Navigation

16. Omega "phase-scanning" for data link
17. VOR "phase-scanning"
18. Time-sharing VOR utilizing common channel (low-cost low-altitude use)
19. Air-to-air proximity warning or spacing techniques
20. RADAR skin tracking
21. Low-cost ILS for General Aviation
22. Omega repeater, Loran-C repeater
23. LF-DF and Consolan
24. Integrated displays, simplified controls, minimum receivers-intermittent transmission
25. Simplified Bell Laboratories dual-tone data-signaling system applied to air-ground VHF transmission
26. Radio altimeter
27. Doppler navigator
28. Standard SSR-ATC transponder with altitude encoding
29. Microwave landing systems.

It is not possible, in this brief study, to establish from this list the best possible technical approach to low-cost general aviation electronics for the 1970-1980 period. However, with careful examination of this technology (that is mostly validated in sufficient detail), the synthesis of a general aviation system that is compatible with the National Air Space (NAS) can take place. Some early first steps typifying the concepts of such near-term system synthesis may help. This should be accompanied by a long-term effort for the 1975-1990 time frame to synthesize entirely new systems.

Currently, for "area-coverage" both VOR (VHF Omni-Range) and a DME are needed. Otherwise, only a few radials of a VOR are available, causing unnecessary concentration of traffic and giving the illusion of "vanishing" airspace. In addition, means are needed of displaying VOR and DME in a map form or on a flight indicator such as the "Omnitrac" or "VAC." Thus, to expand operationally and

to offer more airspace to general aviation which is possible with the simple VOR radial (single Line of Position—LOP—flying), an added airborne DME is necessary. Airborne DME includes a transmitter at L-band, a receiver at L-band, and a new antenna, control head, cockpit display, etc. The airborne DME is generally about twice as expensive and complicated as the VOR. The coordinate converter for mixing the VOR and DME signals (range-angle suitable for pilot display) is similarly costly. Currently, production coordinate converters cost in excess of 10,000 dollars.

Thus, the cost for area navigation can increase by three times compared with that of having only an LOP capability such as a VOR radial. Comparing such equipment, for example, with other equipment designed for localized use of differential Omega signals, the same results can theoretically be obtained with a simple, receiver-only approach that should not only prove to be much cheaper, but can serve at low heights, including aircraft on the surface. This offers the private flyer an important ability to check his equipment with the tower or ATC before leaving the flight line. It avoids the costly air and ground installations needed to provide true, low-altitude VHF coverage. Loran-C can provide functions similar to Omega, but it is more costly. Both systems use low-frequency signals that are not "line-of-sight" limited. This latter characteristic should be of great interest to that portion of general aviation that emphasizes use of the lower airspaces.

Thus, a single receiver could provide this simplicity, since the Omega grid is a series of LOP's that are essentially straight for 100 miles; several sets of LOP's cross each other at oblique angles. The oblique-parallel nature of Omega, its correction with differential signals to an accuracy less than ½ mile, and other features might prove to be an excellent approach for both the low-cost aircraft owner and the government to follow in searching for electronics better suited to solving the serious problems ahead.

⌐. TIME SHARED VOR AREA COVERAGE

Another illustration of this concept is the use of several low-cost, terminal, VOR ground stations that "time-share" by transmitting on a single, common, VOR channel (Figure 1). Not only is the 1000-Mc or L-band DME unit in the aircraft expensive as just noted, but so is the DME ground unit that requires transmitter, receiver, antenna, power, co-located tower units, etc. Thus, if the extension of the VOR-DME coverage were to be such as to assure low-altitude coverage everywhere for General Aviation, more ground sites would be needed.

By time-multiplexing up to eight VOR stations on a common channel—each transmitting for somewhat less than 1 second (much as in the eight-station Omega concept)—several advantages can be obtained by the General Aviation aircraft. The use of multiple VOR (without DME) permits several more ground stations to be installed and VOR coverage to be extended. These special VOR's are now in closer proximity to one another so that, by observing bearings from two stations (or even three stations) simultaneously, an "area-type" coverage and navigation is afforded. Rather than position determination by range and angle to one surface point requiring DME, position determination will be by dual angle computation from two known surface points. The VOR receiver obtains two to three bearings through an eight-station cycle that repeats itself every 6 to 8 seconds. Thus, a full position reading is obtained by reception only every 6 to 8 seconds.

A single VOR receiver provides angles from two or more reference points, requiring storage of the angles as in Omega. The display might well be a simple needle-type instrument normally used in VOR display, but employing one or two added needles so located as to be indicative of the crossing of the angular bearings to the two or three VOR stations. Again, the aircraft equipments to obtain equivalent functions are minimal compared with the current DME, VOR, and coordinate conversion equipments.

NORMAL VOR STATION SPACING

VOR 1

VOR 2

LACK OF LOW
ALTITUDE
COVERAGE

A- LIMITED
DUAL VOR

B- COVERAGE
AT ALTITUDE
REQUIRES TWO
RECEIVERS

SINGLE VOR RADIAL LOP

SINGLE VOR RADIAL LOP

A- CONTINUOUS DUAL VOR
COVERAGE AT LOW AND
HIGH ALTITUDE
B- REQUIRES ONE RECEIVER

VOR 1

VOR 2

VOR 3

VOR 4
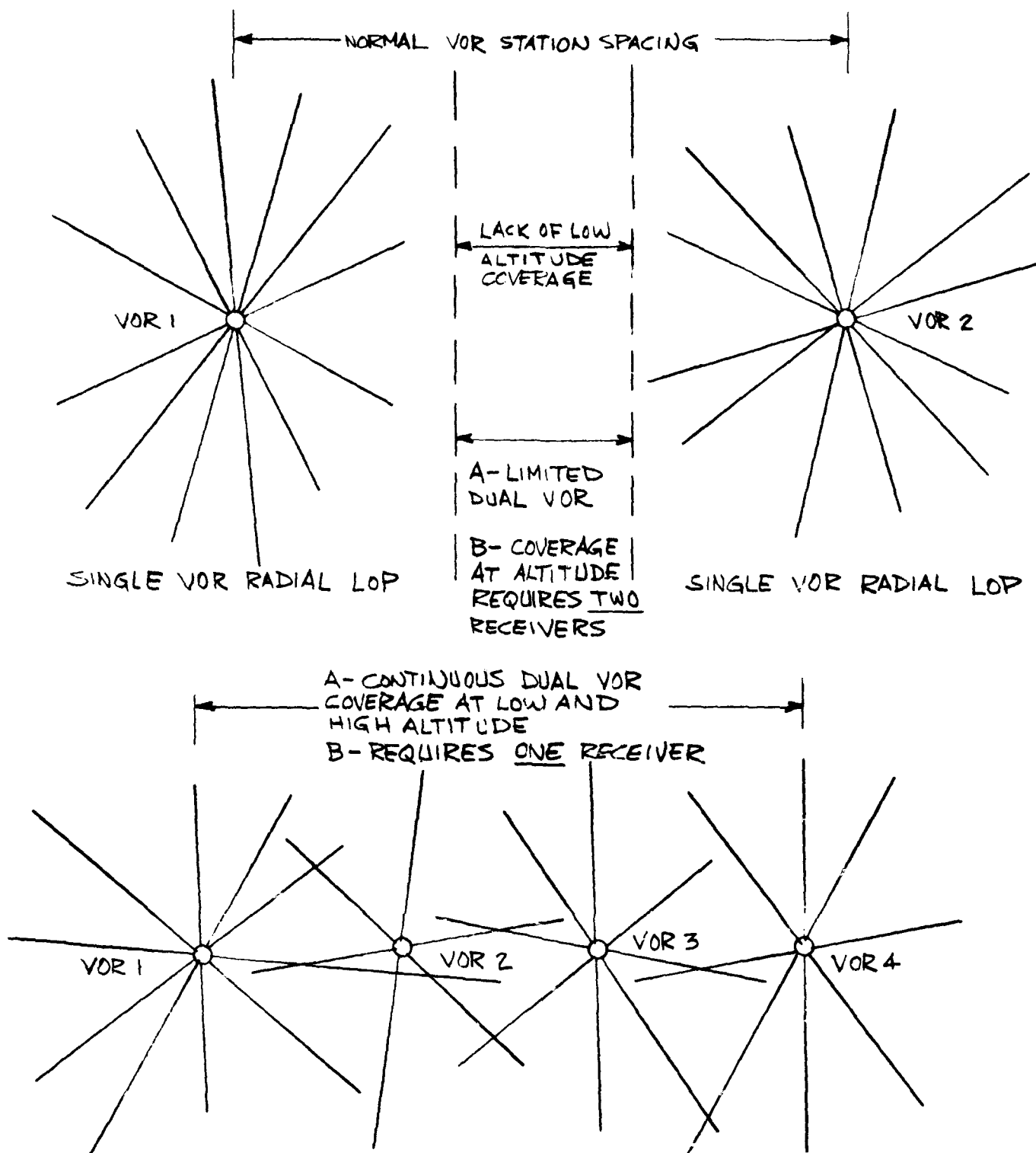
EFFECT OF INCREASING VOR COVERAGE USING SEVERAL STATIONS
TIME-SHARING THE SAME VOR CHANNEL (GROUND COMPLEXITY
INCREASED, BUT AIR COMPLEXITY AND DUAL LOP'S PROVIDED)

FIGURE 1

There is also the possibility that the concepts of a low-frequency oblique parallel grid system can be combined with a radial grid system such as the VOR. In other words, by integrating the two in the general aviation aircraft, not only would the differential, local corrections be provided the aircraft as it uses the Omega LOP's, but Omega is operationally equivalent to a DME referenced to the VHF station. This can all be done by programmed aircraft reception, avoiding the generally messy business of transmitting several signals from the aircraft, reception on the ground of these signals, and the need for a special ground facility to return DME transmission signals to the aircraft.

G. COMBINED VHF/VLF SERVICE

Although one might argue that Omega could do the entire job, it is suggested that the combination should also be considered, because it has several distinct advantages (Figures 2, 3, and 4).

1. All tracks are referenced to the NAS grid system of VORTAC.

2. DME is avoided by general aviation.

3. VOR transmission path (voice or time-sharing) can provide continuous, updated Omega corrections.

4. The oblique-parallel grid combined with a radial-line grid permits several concepts of "position-roll-call" suitable for a simple data link.

5. The grids could be used for position reporting by some aircraft in place of an SSR system. The coordinate conversion for interfacing with the normal SSR ground processing equipments would be minimal.

6. Selective calling to a specific aircraft, such as a data link or even a voice message, could be done on a simplex channel as the full coordinate position of the aircraft is evident to both the pilot and the ground controller.

7. The combined VHF/VLF service would unburden many of the complex concepts of the data link and result in a simplified data message format suitable for the existing VHF voice bandwidths. It could perhaps use voice and a simple tone system such as the "touch-tone," dual-tone, coded data transmission of the Bell system.
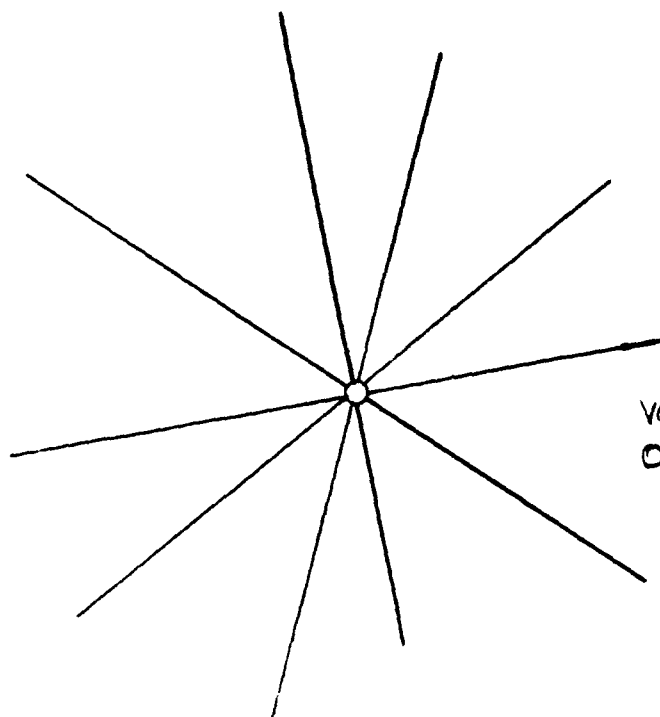
VOR WITH RADIAL LINES
OF POSITION (LOP'S)
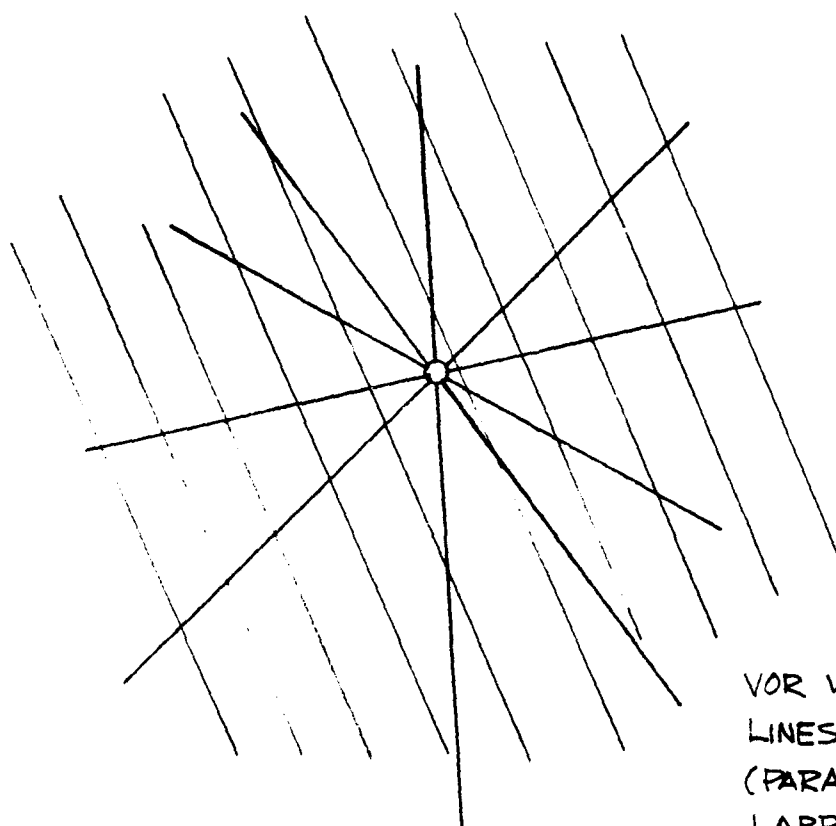
VOR WITH ONE OMEGA
LINES OF POSITION,
(PARALLEL LOP'S OVER-
LAPPING RADIAL LOP'S)

EXAMPLE OF COMBINATION OF OMEGA LOP AND VOR LOP

FIGURE 2

VOR AND OMEGA
LOP NO. 2

VOR AND OMEGA
LOP'S NO. 1 AND
NO. 2

VOR AND OMEGA
LOP NO. 1
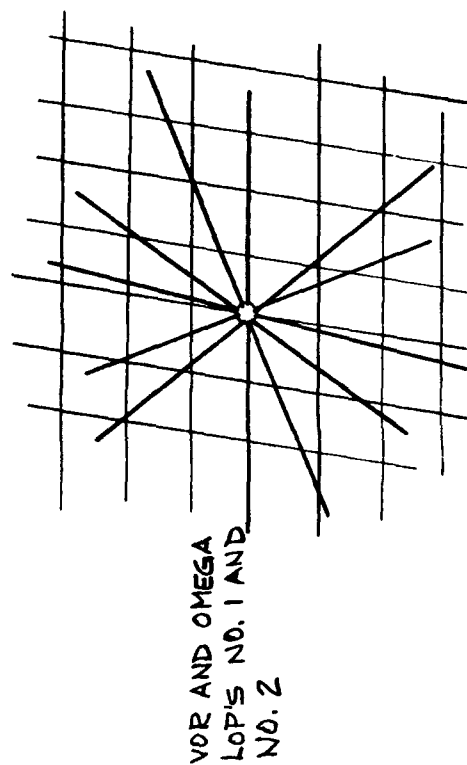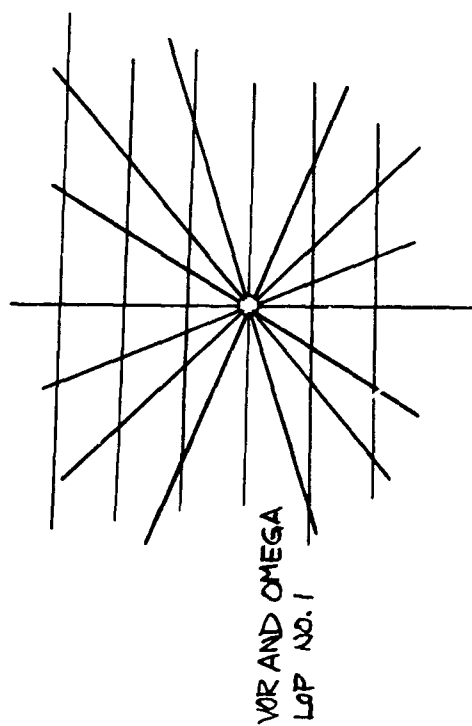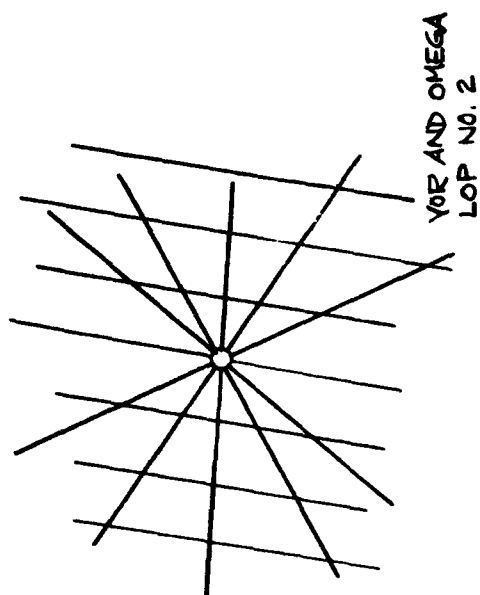
COMBINATIONS OF OMEGA LOP'S (OBLIQUE-PARALLEL) WITH
VHF OMNIRANGE LOP'S (SINGLE-POINT RADIALS)

FIGURE 3

23
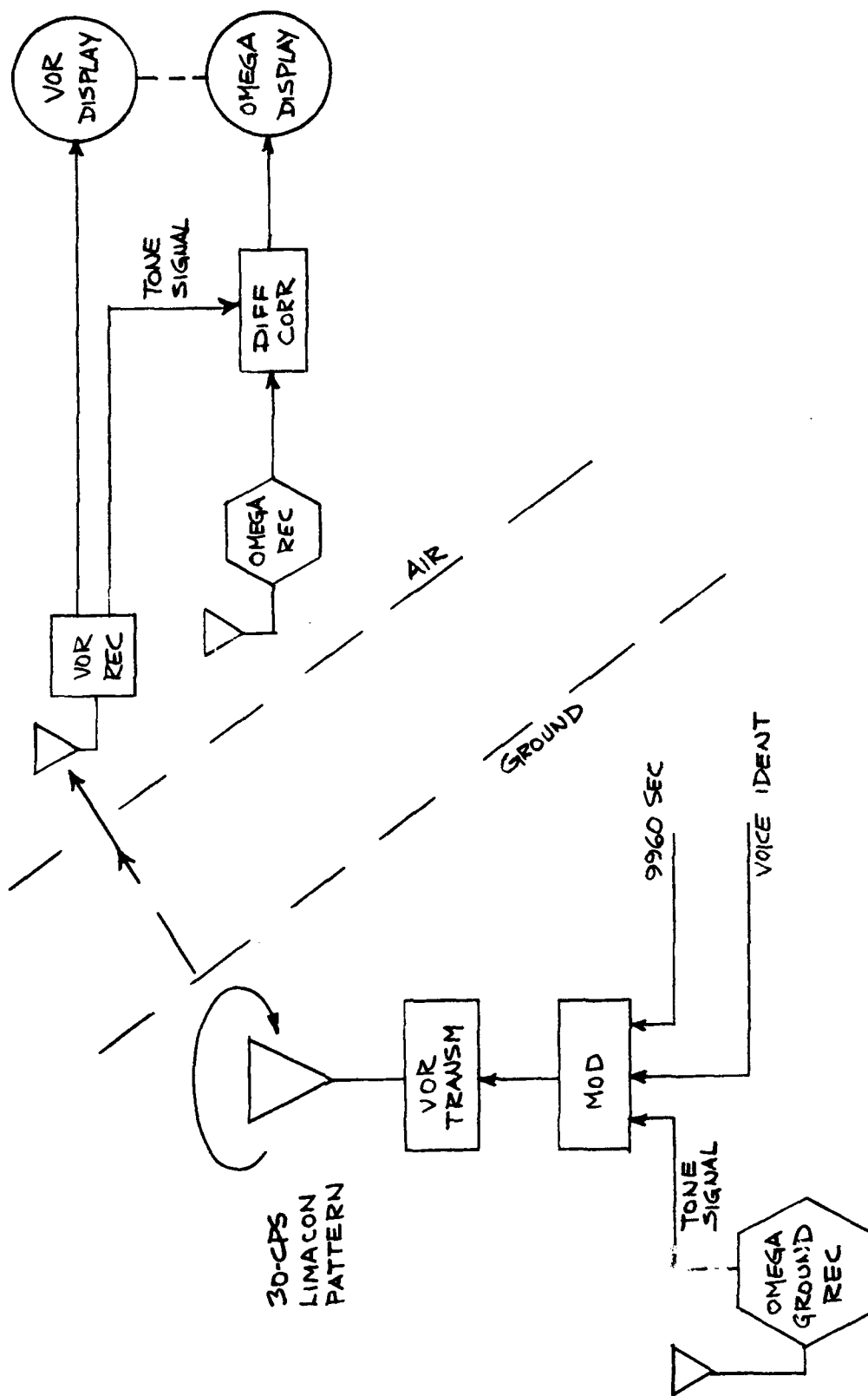
USE OF VOR LINK TO AIRCRAFT FOR TRANSMISSION OF OMEGA DIFFERENTIAL SIGNALS PROVIDING
COMBINED RADIAL-PARALLEL OBLIQUE GRID REFERENCED TO VOR STATION COORDINATES

FIGURE 4

8. The precision time references provided by both the Omega and the VHF transmissions could be used for air-to-air spacing, proximity reporting, and ranging.

9. A position and time-ordered roll-call would permit a pilot to determine whether other aircraft are near him for collision avoidance without his actually using active electronics as most collision avoidance systems (CAS) require.

10. The simplicity of equipment would allow a ground display of traffic of the minimum-equipped, general aviation aircraft at general aviation airports. The current ASR-4 and-5 radar programs are out of the financial reach of the small air field. A display system for perhaps a few thousand dollars could be available, since the signals of the oblique-parallel or range-angle grids used for navigation and the interrogation signals for identification and data transmission could be used directly on the display.

For No. 10 above, a simple air-to-ground message can be sent in less than 0.2 second using the Bell tone system. This would mean that 50 aircraft could be serviced each 10 seconds. This will probably provide adequate updating of a ground display, being generally commensurate with the speed and maneuvering capability of the vast majority of low-cost general aviation aircraft. The details of a tone data-link are covered in paragraph J of this section.

H. FURTHER EXAMPLES OF CANDIDATES FOR SYSTEM SYNTHESIS

Again it should be noted that the above specific configurations of general aviation systems are not urged but given primarily as examples and candidates for the synthesis process that must take place if a near-term capability equivalent to the current 25,000 dollar airborne electronics package is to be achieved for perhaps less than 5,000 to 10,000 dollars.

The list of potential technology should be examined and tested to determine whether an integrated, overall means of achieving the desired results with a complement of possibly two receivers and two transmitters is realizable. The modulation and demodulation circuits that might use a common transmitter or receiver must be

considered for multi-functional purposes. Interestingly enough, this has happened to some extent in VHF, such as the 90- and 150-cps modulation used on both glide slope and localizer, and by channelization of the adjacent bands of VOR, localizer, and tower communications. Some modulation and processing commonality of tones, intermittent CW, digital and analog circuits can exist with modern circuit design. In order to further illustrate these possibilities, some of the numerous items listed in paragraph E of this section will be further discussed. The use of a "tone" DME is a good example. This consists of a single or dual-tone modulation frequency transmitted over a two-way link and received back at its origin where phase angle between the oscillator and returned signal is related to distance.

1.   VHF Tone-DME

        From time to time in the past, equipments have been built that multiplexed a tone on a VHF facility such as a communication circuit, localizer, or VOR. Wright Field engineers first did this during World War II, using a tone of around 2,000 cps and a transmission period of 1/25th of a second every 2 to 3 seconds. This signal, though intermittent, is simply stored and smoothed, providing effectively a continuous DME indication. The use of a Tone-DME with the time-sharing stations of several aircraft on the same ground-to-air channel is necessary. With a conventional VOR the programming of the VHF transmissions from the aircraft (using the communications channel) would be achieved by roll-call methods using sequential azimuthal or assigned time slots.

        Let us assume that 10 seconds is allowed for a simple device to report by transmission "time-slots" that are programmed by the angle from North; these time slots report multiple aircraft and their VOR bearings. Accordingly, an aircraft at 90 degrees would measure its distance at 2.5 seconds, one at 180 degrees at 5 seconds, one at 270 degrees at 7.5 seconds, etc. This provides a

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time-ordered transmission sequence that is geographically distributed, thus minimizing interference since two aircraft at the same time would be at the same azimuth. This scheme also offers an air-to-air feature, since two aircraft at the same azimuth reply at the same time. Such a DME tone would be re-transmitted on the voice channel of the VOR, providing a total system bandwidth well within the normal band pass of the equipments. Various choices of the origin of the tone (air or ground) and two-way or three-way paths to provide DME at either or both terminals are open to the system designer as shown in Figures 5, 6, and 7.

This scheme uses the equipments that are normally used for VOR and communications, adding a phase comparator and indicator; it is far simpler than the 1,000-Mc pulse DME of the ICAO standardized, 200-mile type. The general aviation Tone-DME would be limited to a range of about 40 to 50 miles.

2. Time Sharing VOR Techniques Multiplexed with Other Functions

As noted previously, modern electronics can utilize a much longer data rate than was originally considered necessary in the design of the VOR. The continuously available data, requiring the full-time utilization of a scarce VHF channel is by today's standards quite wasteful of radio spectrum. About 60 to 80 channels are used for "channelizing" the approximately thousand VOR stations in the United States. These channels are repeated at great distances, beyond the radio horizon, so that they do not interfere with one another. By permitting a VOR station to transmit bearing information for about 0.70 to 1.0 second, the receiver AGC settles, and a bearing is available. If this station then terminates its transmission or utilizes the next few seconds for some other function, the airborne memory of the bearing data is adequate for the normal use of VOR data.

Although this lowered rate could not be tolerated, say in a final landing approach where precision to a few feet is

NF = normal functions
R = receivers for VOR, ILS, communications, ADF, etc.
T = transmitters for VOR, ILS, communications, ADF, etc.

SIGNAL PATH IS 1-7
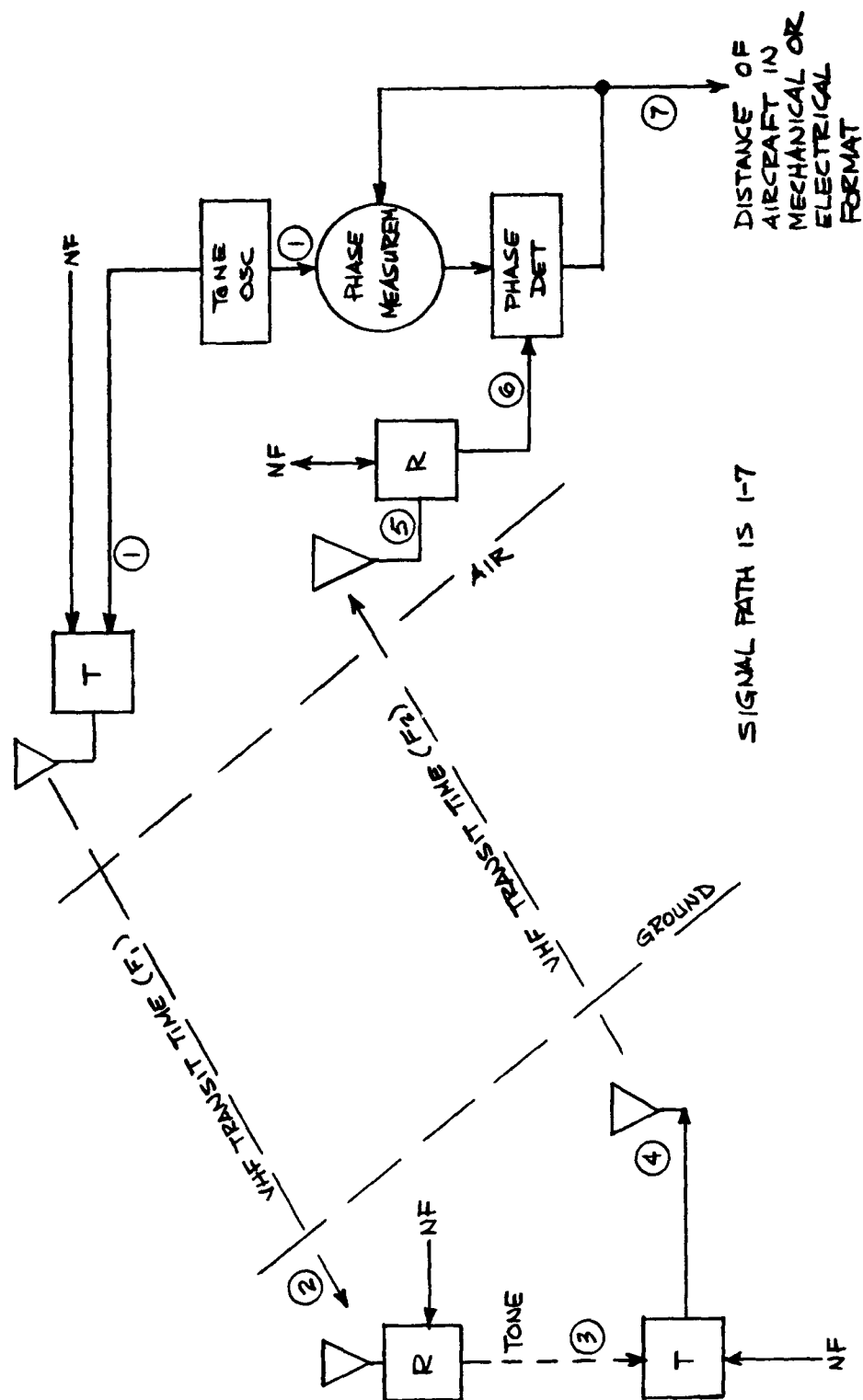
TONE DISTANCE MEASUREMENT (OUTPUT AT AIRBORNE SOURCE)

FIGURE 5

28

NF = normal functions
R = receivers for VOR, ILS, communications, ADF, etc.
T = transmitters for VOR, ILS, communications, ADF, etc.

NF

NF

R

TONE

③

④

T

⑤

AIR

VHF TRANSIT TIME (F2)

⑤

VHF TRANSIT TIME (F1)

②

GROUND

⑥

NF

R

TONE

⑦

INDICATION OF RESPONSIVE
AIRCRAFT (ELECTRICAL FORMAT)

⑧

②

①

NF

T

TONE
OSC

①

PHASE
MEASUREM

①

PHASE
DET

SIGNAL PATH IS 1-8
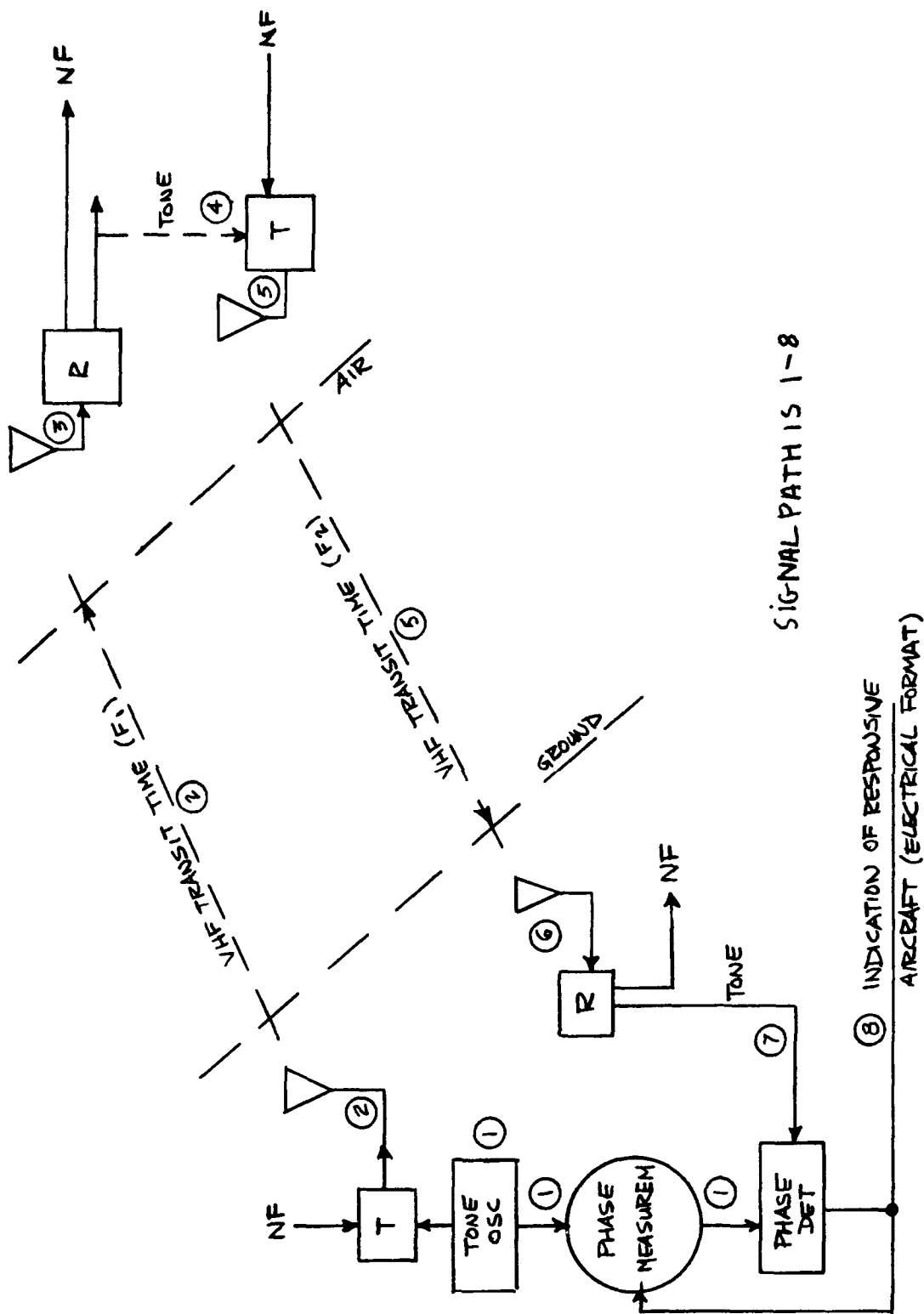
TONE DISTANCE MEASUREMENT (OUTPUT AT GROUND SOURCE)

FIGURE 6

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Tone DME with AIR and GROUND
indications from same aircraft
using dual tone 4 x 4 two-digit
signaling (256 increments)

(signal path is 1-13)
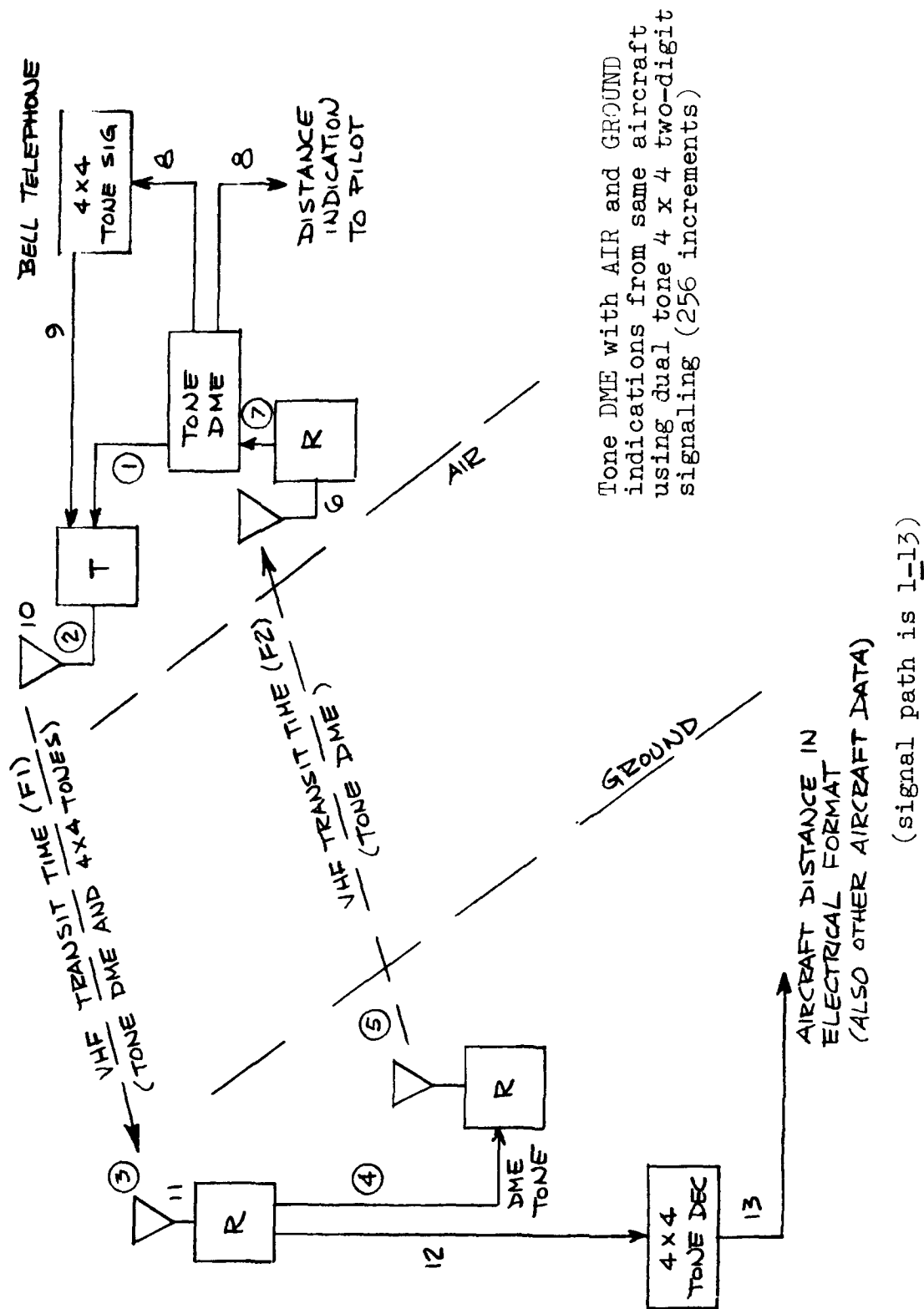
TONE DME WITH AIR AND GROUND OUTPUTS

FIGURE 7

important and rapid updating is essential, the VOR system is not
so demanding. It is accurate to about ±4 degrees in general aviation
aircraft (Report RD 65-98 FAA). This ±4 degrees is equivalent to
about ±1 mile at 14 miles from the station and ±2 miles at 28 miles
from the station. The RSS (root sum square) value for errors in-
cludes the aircraft, ground, and usage errors. It is typical of
the end product of general aviation usage of VOR. Thus, although
precision measured in feet is involved in ILS landing accuracy,
usually only thousands of feet are involved in VOR air-route accuracy.
At a ground speed of about 3 miles per minute, a sample every 10
seconds should be more than ample, being commensurate with the
overall accuracy and instrumentation of the aircraft. In 10 seconds
the aircraft would probably move about 3,000 feet or ½ mile. This
is less than 20% of the operational accuracy of the VOR at 28 miles.
Some VOR flight testing of this concept has been conducted.

Thus, during the next 8 seconds of a 10-second time-
sharing concept, the VOR station could transmit on a second channel
a Tone-DME, limited data link messages, etc. One scheme is to
arrange by means of telephone circuits to sequence eight VOR stations
on the same channel for about 1 second each, within a total cycle
time of 10 seconds, thus permitting eight times the utility of a
given channel (Figure 8). It is probable that the general aviation
aircraft would not know that the duty cycle of the VOR signal
activating the course deviation indicator (CDI) was operating with
less than a 12% duty cycle. Reception of the Omega worldwide
signals could also be used for the synchronization between VOR
and Omega using the same time base, thus eliminating the land wire
or phone line interconnection.

If only three channels (5%) were set aside from the 60
to 80 channels now devoted to the VOR channelization scheme, essen-
tially 24 new channels for general aviation usage would be required.
With commercially available "packaged" VOR station installations
available for around 10 to 20 thousand dollars, this would offer

VOR S₁   VOR S₂   VOR S₃

VOR S₆   VOR S₅   VOR S₄

S₁ TO S₈ SITE LOCATIONS

VOR S₇   VOR S₈

EVEN | S₁|S₂|S₃|S₄|S₅|S₆|S₇|S₈| S₁ | S₂|S₃|S₄|S₅|S₆|S₇|S₈| S₁   S₈|

0   10   20   SECONDS

OMEGA |S₁|S₂|S₃|S₄| | |S₈| | | | | | | | | |

.9   1.1   1.1   1.2

1.0   1.2   0.9
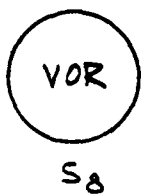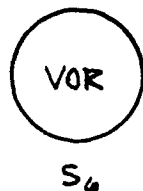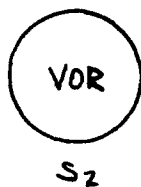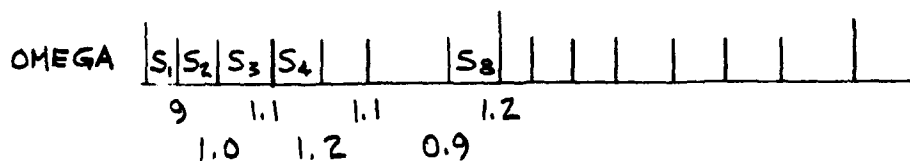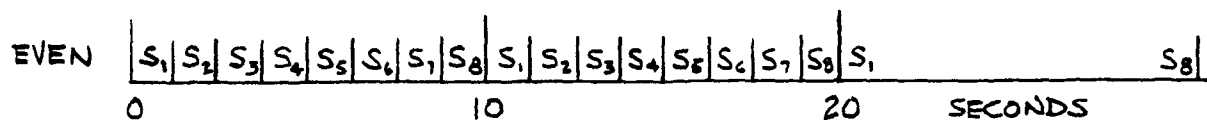
EVEN SPACINGS WITH TONE IDENTITY OR TIME CODED TRANSMISSION
PERIODS (SUCH AS OMEGA) ALLOW AIRCRAFT TO SELECT A SINGLE VOR
WHOSE STORED SIGNAL IS DISPLAYED AS NORMAL VOR (UPDATED EACH
10 SECONDS).

SEVERAL VOR STATIONS TIME-SHARING A COMMON CHANNEL

FIGURE 8

general aviation a source of more navigational service and "area" service (within existing radio frequency assignments). Not only would the restrictions now imposed on channels be lifted, but a special, lesser grade service offered, using the lower-cost packaged VOR ground stations (such as Wilcox), and airborne equipments that do not require large channelization capacity. In fact, the channelization over a large number of crystal-referenced channels is avoided, which represents an important part of the cost of the VHF airborne equipments.

Perhaps the greatest advantage of a single-channel, multiplex station, time-shared VOR system is that with close spacing of the ground units, dual bearings are available from the same receiver automatically without switching or requiring the use of a second VOR for cross-bearing information, Figure 9. The outputs can be increased often to three stations at no sacrifice to the airborne equipments. This would give an "area-type" coverage since the pilot would have three cross-bearings available to him by reception on a single channel only (Figure 9).

Use of an instrument such as the CDI with three needles geometrically pivoted to provide by their crossings the analog representation of the aircraft position is one possibility of a simple cockpit display (Figure 10). This time cycling example was chosen purposely to be the same as the time cycling of Omega. Both the VOR time sharing and Omega time sharing concepts have been tested and flight validated. There are several interesting interrelationships that can now exist between Omega LF signals and a VOR signal whose formats and sequencing have been integrated for the maximum of utility with the minimum of cost. Some simple engineering changes in VOR receivers would, of course, be needed but the resultant cost (perhaps 10%) would be relatively low compared with the service provided.

Receiver using Signals from Site 2
would automatically switch to Channel
A during time slot T and then to
Channel B during time slot S. AM
'capture' should eliminate radiation
from site 9. Dual-tone data trans-
mission, proximity signals, etc.,
can utilize remaining slots.

(1)   (2)   (3)   (4)
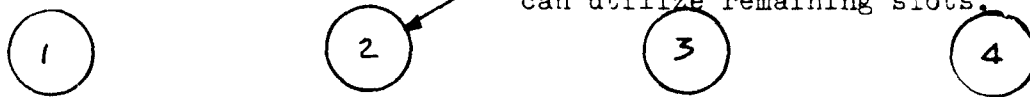
Geographic Distribution of
VOR Time-Shared Ground sites

(5)   (6)   (7)   (8)

(9)   (10)   (11)   (12)

|←———— 10 SECONDS ————→|

VOR CHANNEL A	1	2	3	4	5	6	7	8	1	2	3	4	5	ETC.
TONE DME CHANNEL B	2	3	4	5	6	7	8	1	2	3	4	5	6	ETC.
VOR CHANNEL B	9	10	11	12	ETC.									
	S	T	U	V	W	X	Y	Z	S	T	U	V	W	X

O = TIME SLOTS ——→
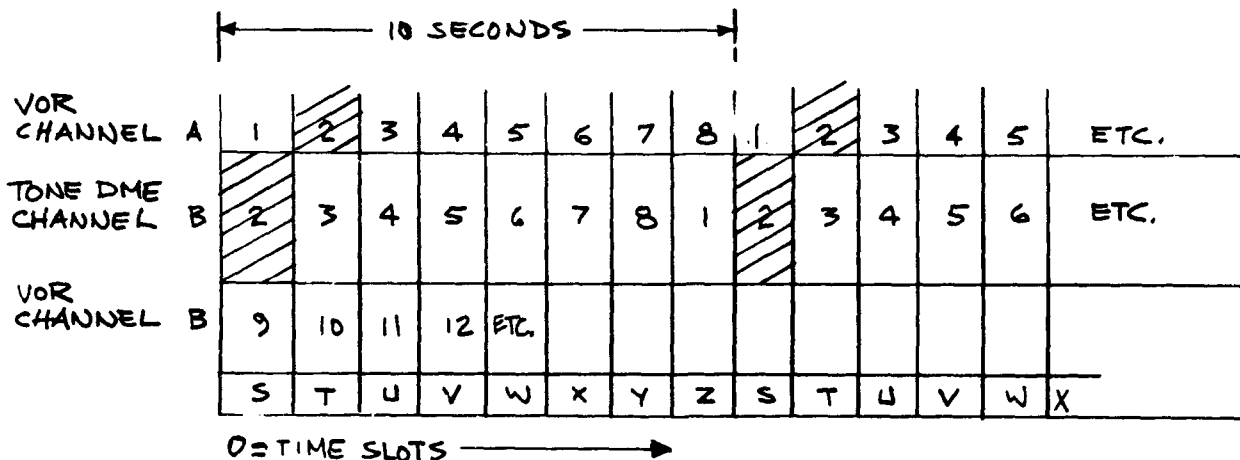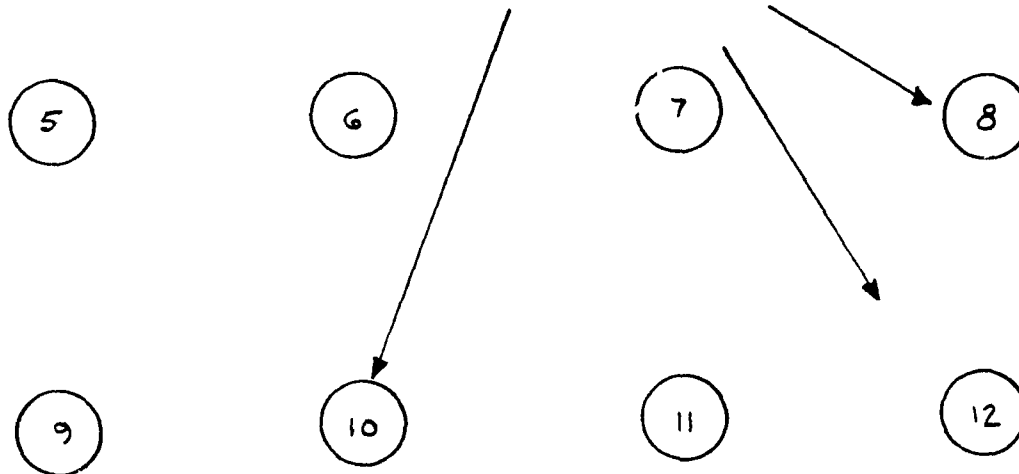
ONE METHOD OF GEOGRAPHIC SEPARATIONS AND TIME SHARING ON TWO VOR CHANNELS TO
PROVIDE FUNCTIONS OF ANGLE AND DISTANCE FROM A MULTIPLICITY OF GROUND SITES

FIGURE 9

34
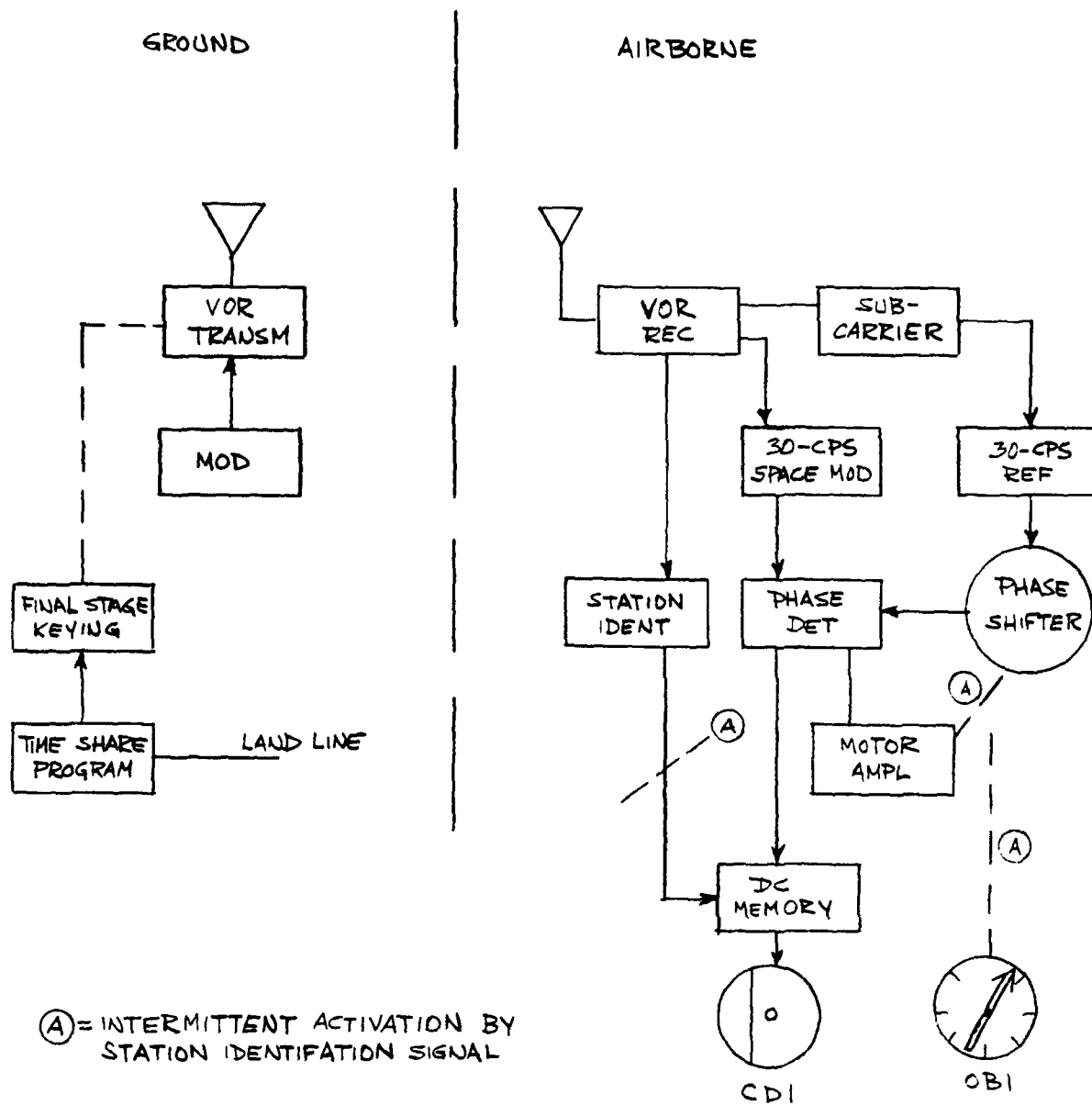
STORAGE OF INTERMITTENT VOR BEARINGS
USING SERVO MEMORY AND/OR DC MEMORY

FIGURE 10

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3. Landing Approach for General Aviation Aircraft

As noted, it will be impossible in the near future to fully replace the VHF elements of general aviation. They are too valuable; they have been engineered into low cost units and within their capability should be integrated with newer elements that can enhance the functions that can be derived from an already existing VHF capability. The needs of the low-cost general aviation electronics requirements are at present best considered at VHF rather than UHF or L-band. In addition to the previous examples, such as time-sharing several VOR signals on a common channel, integrating Differential Omega to give a DME and ATC function with the VOR, another case is evident in the instrument low-approach case. The VHF channelization fortunately includes in the same airborne units the VOR phase circuitry and the amplitude (90 to 150 cps) modulation circuits of the ILS.

Low-cost, low-power, solid-state, ILS ground units are becoming available. These have reduced the cost of an ILS installation to perhaps one-third of its past costs and result in more reliable service, since solid-state low-power drain units (capable even of battery operation) can be installed at many runways used by general aviation. This progress suggests that the general aviation pilot will have available at least the VHF-Localizer at many more fields (in the 1970-1980 period).

The UHF-ILS glide slope has several deficiencies in the ground element, and requires a costly independent airborne unit (operating at 330 Mc rather than 110 Mc) that is used for no other purpose. The previous suggestion of using a Tone-DME with the VOR station is equally valuable when considered with the VHF-Localizer station. The DME signals will not interfere when multiplexed with the normal (90 and 150 cps) beam modulation. This is true because the two signals are separated by a ratio of at least ten to one, allowing excellent filtering. The ILS voice channel could convey the intermittent Tone-DME (say, using tone transmissions 1/30th of

a second long) repeated every 1 to 2 seconds. This would permit
a theoretical common channel time-sharing for 30 aircraft with
continuous updated information. Normally only about 5 aircraft
will be approaching on a localizer at any one time; thus, traffic
handling on the time-sharing circuit should be no problem.

The pilot utilizes the VHF localizer for runway align-
ment and his Tone-DME and altimeter for a computed let-down glide
path (Figure 11). This would be computed to a point near the
runway threshold rather than at the roll-out end where the localizer
is situated. The use of a marker beacon would aid in double-checking
the readings at some critical height such as 200 to 300 feet.
Currently, it is the practice to locate the middle-marker at a
given distance to achieve this height check (about 3,500 feet from
threshold). The marker can also be made to be more useful to
general aviation than it is today, without any change in the air-
borne 75-Mc equipments. A radio signal could correct any barometric
errors using an "inverse" radio altimeter.

Another possibility along this same line is the use of
the Omega grid in place of the VHF-Tone-DME for a range determina-
tion element differentially referenced to the runway. By resetting
and aligning the Omega signal (differential Omega) at the outer
marker or by a differential setting from the VHF localizer (voice
channel) itself, a simple tone-data message would automatically
update the Omega receiver, removing the diurnal error continuously.
The Omega should then be accurate to about 0.2 to 0.3 NM according
to such tests by the Navy. The Omega signal correction would be
updated on the approach so that the final Omega reading is more
nearly a "Rendezvous" accuracy (both receivers in the same environ-
ment).

Even with a 0.25 NM error, while following a 5-degree
glide path (small aircraft use steeper angles), a height error
(about 1/10th this value) of 100 feet is encountered. This, coupled
with the typical altimeter errors (assumed also at 50 to 100 feet)
should provide a realistic 300-foot ceiling for slow, light aircraft
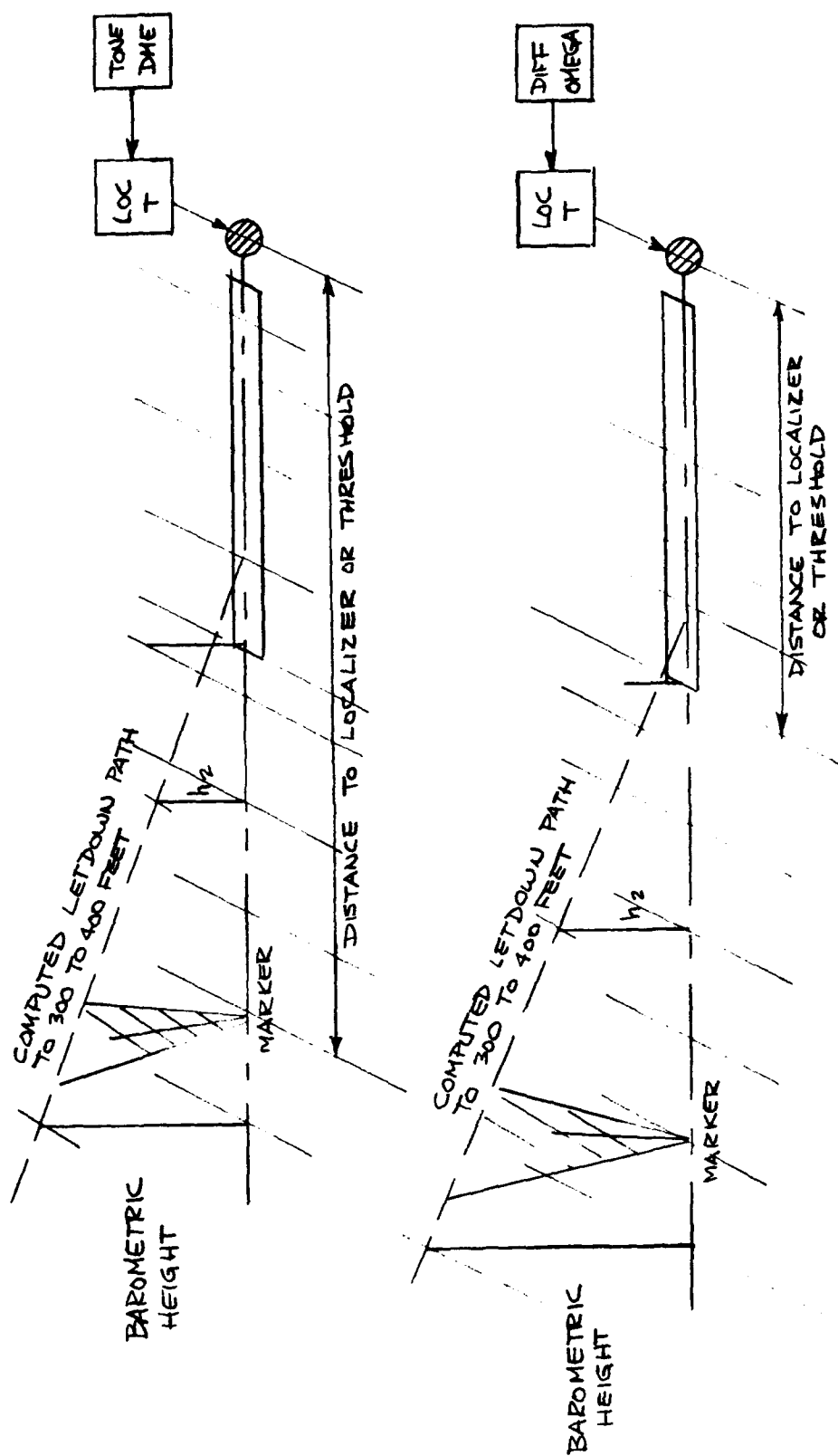
USE OF LOCALIZER–ONLY FOR INSTRUMENT APPROACH FOR GENERAL AVIATION

FIGURE 11

landing on a runway. Furthermore, the pilot can select an angle
that is computed for his aircraft's best flight performance. The
conventional 2.5-degree paths may prove to be too flat for the
single engine aircraft in an approach configuration. Furthermore,
a steeper angle assures better clearance over approach obstacles,
and more fields can be qualified for IFR approaches. New criteria,
however, are needed, since the ICAO-FAA (TERPS) criteria for ILS
assume a 2.5 or 3.0 degree glide path. Several tests by USAF on
"let-down" computers should prove helpful to check out these new
criteria.

4. Collision Avoidance Using Navigational Data

Most of the current CAS that have had some flight testing
still leave several questions unanswered and appear to cost in the
range of 30,000 to 40,000 dollars. As noted previously, the basic
electronic needs in today's general aviation market can be as high
as 25,000 dollars, excluding any specialized airborne units for
CAS, data transmission, or ILS. Thus, a total of over 50,000 dollars
is implied. The problem of achieving even the basic electronic
needs has been discussed previously and the potential of installing
a CAS system suitable economically and operationally for general
aviation aircraft, is far from realization.

Yet, the very fact that an IFR capability for thousands
of aircraft may become a reality because of the lower cost IFR
navigational electronic package developed for general aviation, one
must consider to what extent these aircraft now become potential
collision hazards to the airlines, military, and other general
aviation aircraft. Since it is probable that even the smallest of
light aircraft can, upon colliding with a jet, damage it sufficiently
to cause it to crash, one cannot assume it is something like trying
to protect a large dump-truck from a Volkswagen. Several sensitive
mechanical areas exist in a large jet of even the 747 proportions
that can cause loss of control when struck by an object weighing
a thousand pounds or more.

The best low-cost, immediate solution to the collision problem is the SSR beacon using a potential "listen-in" feature for proximity warning but still placing the prime responsibility with the ground (air-traffic) authority to continuously compute position data. An alternative or even complementary method is suggested wherein a grid navigation system is used such as the differential Omega system with its oblique parallel lattice lines. Each aircraft on a time-sequenced schedule using the lattice of Omega for the sequencing, radiates a simple, short, two-tone signal such as those used in the "touch-tone" dialing of the Bell system. This concept assures planners that the ground data transmission will be inexpensive and can be fed directly through low-cost phone lines to ground computers (Figure 12).

Perhaps even more important, the aircraft can "hear" each other in the process of the automated position reporting. For example, if a low scan-rate is used, the pilot need only listen in when the signals of his own aircraft are being transmitted; listening on either side of the transmission time will assure him of the presence or absence of another aircraft. Such a signal appearing before his transmission indicates that the aircraft is in one direction on the Omega LOP-1; later, it indicates that the aircraft is in the other direction. Listening on the transmission cycle of the LOP-2 with similar observations, the pilot can then determine the two coordinates of the other aircraft.

Similarly, even twenty dual-tone codes assigned to altitude might be very useful. The pressure differentials are greater for, say, a 1000-foot change between 1000 and 2000 feet than between 30,000 and 31,000 feet. This is an advantage to the low-cost general aviation aircraft in semi-automated reporting of their altitudes.

Further details on tone signaling are given in paragraph J of this section.
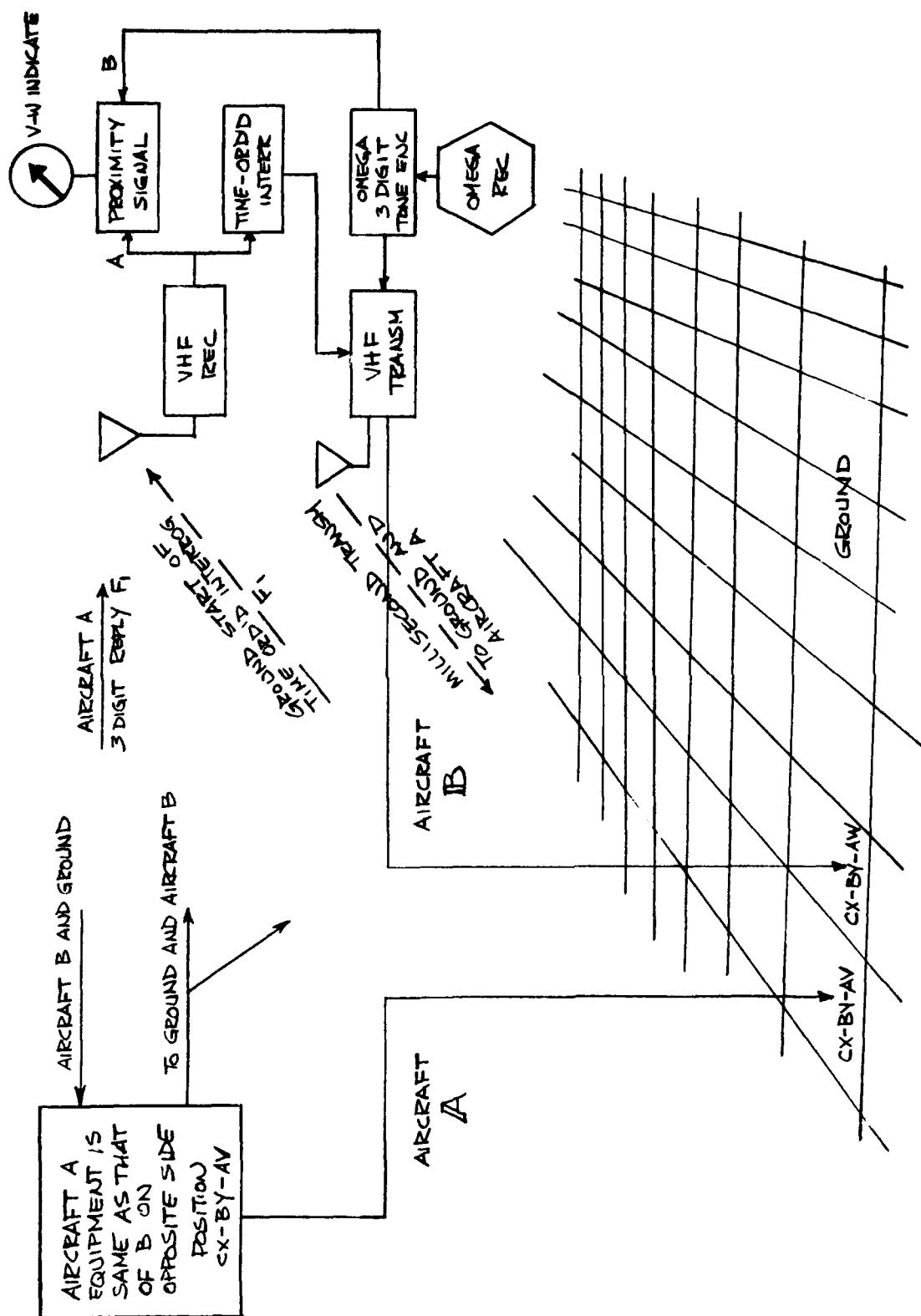
POSSIBLE INTEGRATION OF TIME-ORDERED POSITION REPORTING OF OMEGA COORDINATES FOR GROUND DISPLAY, PROCESSING, AND PROXIMITY SIGNALING TO AIRCRAFT IN ADJACENT POSITION

FIGURE 12

Altitude readouts each representing 500 feet up to 5,000 feet would permit the simplest form of height reporting. This would be a direct pick-off from the normal barometric altimeter avoiding the sophisticated altitude transmission equipment of the SSR that calls for the 4,000 codes to be assigned in 100-foot increments to heights of around 70,000 feet. The cost of the precision altimeter and the SSR encoding scheme is sufficient to essentially eliminate the low-cost general aviation aircraft from the service; yet this is the very aircraft that is often of greatest concern.

The use of the fine-grain, SSR data for height, identity, and position of fully equipped users would be beneficial since any potential hazard either noted in the cockpit or by ground monitoring and surveillance would result in "clearing" reasonable airspace around the general aviation aircraft. In so doing, the aircraft cooperating would not be unduly diverted because of the high resolution inherent in the SSR system.

This is one suggested way to encourage the general aviation aircraft operator to cooperate in the overall scheme of ATC and IFR flight, but at a low cost and commensurate with other highly equipped aircraft. Fortunately, the high-performance jets utilize the upper airspace assignments, and the single-engine piston aircraft that are so numerous are thus naturally separated from them.

I. AN INTEGRATED ELECTRONICS PROGRAM

It is probable that unless both near-term and long-term integrated and evolutionary plans are formulated, tested, and implemented, the desired results of improved and lower cost IFR, ATC safety, ATC capacity, and other functions will not be achieved. As an example of the potential of integrating elements in a "total" approach to the problem rather than an electronic unit or system to solve each problem, the following is suggested. The airborne complement consists basically of a VHF navigation receiver, VHF communications receiver, a VLF Omega receiver, and a VHF-transmitter (Figures 13 and 14). It is obvious from many previous equipment

AIRBORNE UNITS

Column headers: LANDING, NAVIGATION, PROXIMITY, POSITION REPORT, ATC, IDENTITY, VOICE COMM, VOR RADIAL, AREA FLIGHT, PATH COMPUTE, ALTITUDE REPORT, AIR TO AIR SIGNAL, GROUND DISPLAY, GROUND DATA TRANS, NON-AIRWAY FLYING, TIME ORDER ROLL CALL, DISTANCE MEASUREMENT

A — VOR-LOC REC

B — VHF COMM REC

C — VHF TRANS

D — TONE DME CIRCUITS

E — 4 × 4 TONE SIG

EXAMPLE OF VARIOUS FUNCTIONS PERFORMED BY A VHF-ONLY
COMPLEMENT OF LOW-COST GENERAL AVIATION AIRBORNE UNITS

FIGURE 13

	A	TYPICAL COVERAGE (MC)		B		C

A — TYPICAL COVERAGE (MC)

1 VHF COMM REC   118-136

2 VOR LOC. REC   108-112

3 VHF TRANSM   118-136

4 GLIDE PATH REC   330-335

5 DME   960-1150

6 SSR TRANSP   930-1090

7 MARKER REC   75

8 ADF REC   BELOW 500 kc

9 DATA LINK   VHF, UHF OR MICROWAVE

10 PWI OR CAS   FREQUENCY NOT DET. (POSSIBLY 1600 Mc)

B

1 VHF COMM REC

2 VOR LOC. REC

3 VHF TRANSM

4 FUNCTIONAL MULTIPLEXING
A - 4x4 TONE
B - TONE DME
C - INTERM TRANSM
D - OBI STORAGE
E - ROLL-CALL
F - ENCODING

C

VHF COMM AND VOR REC

VHF TRANSM

OMEGA REC

FUNCTIONAL MULTIPLEXING
A - 4x4 TONE
B - TONE DME
C - INTERM TRANSM
D - ROLL-CALL
E - DIFF SIGNAL
F - ENCODING

A - PRESENT TRENDS
B - VHF ONLY POSSIBILITY
C - VHF AND VLF POSSIBILITY

EXAMPLES OF SYSTEM INTEGRATION TO REDUCE GENERAL AVIATION ELECTRONIC
COMPLEXITY AND COSTS WHILE INCREASING FUNCTIONAL VALUES
FIGURE 14

designs that since all the VHF functions will be essentially CW, using voice or tone, that a transceiver design for all the VHF functions would aid considerably. A frequency synthesizer suited to providing three frequencies, a common power supply, duplicate IF units, and modular design would aid in the VHF package. Several new requirements that could easily be met with respect to delay (phase-shift) through the receivers, adding Tone-DME, and the modulation multiplexing of an intermittent, dual-tone data-message system, should all be included in the modernized and integrated VHF package. Rapid, intermittent VHF transmission will be needed lasting for 1/30th to 1 second every 10 to 20 seconds or as needed. A single VOR receiver designed for measuring and storing 2 to 3 VOR bearings is included (Figures 13 and 14).

The Omega receiver is basically the new element. It is suggested in this example since it can possibly void the SSR beacon, DME, data transmission, and CAS or proximity warning indicator functions which are yet to be added to achieve IFR and ATC in most low-cost general aviation aircraft. The interrelationship of the VLF Omega signals with VHF will hopefully reduce the need for most of these added elements as well as the glide-slope receiver.

Thus, one package is an integrated VHF transceiver (navigation and communications) and the other is an Omega receiver.

J. **DATA TRANSMISSIONS**

Although many so-called "data links" have been developed by the military services and the FAA, such as the 5-kc time-division system and the frequency-multiplexed system, each of these data links is rather complex in certain ways. Even with large-scale production, they are far too costly and complex to be suited to the general aviation market. The need for a rather simple data link has been stressed elsewhere in this report, and some suggestions that the Bell Telephone system, known as the "touch-tone" system of dual-multi-frequency signaling, might apply are worthy

of consideration. This system has the advantage of years of
detailed research, testing, and reliability engineering so that
if it is useful on a VHF channel, little or no development costs
are involved. Simplicity is one of its main virtues. Its success
since about 1963 indicates that the entire Bell system will be
changed over to the system.

The fact that the entire national network of wire communi-
cations can carry the same data-message formats as used for air-to-
ground data signaling of general aviation aircraft is in itself an
important factor to consider in system planning.

Basically the Bell multi-frequency signaling system
(touch-tone) consists of a very simple unit at the transmitter
weighing a few ounces that generates up to 16 unique signals, each
composed of 2 tones that are simultaneously generated for transmission.
This is basically a "4 X 4" tone system composed of 4 tones in a
"low" group (697,770,852 and 941 cps respectively) and 4 tones in
a "high" group (1209,1336,1477, and 1633 cps respectively). All
figures are given in cycles per second (Figure 15). The pushing
of a button results in the joint selection of one tone from the
low group and one tone from the high group; these tones instantly
and simultaneously generated.

Bell Laboratories developed an ingenious arrangement
of two, simple, tapped, resonant inductors in a transistor-oscillated
circuit. Both tones are generated by the same oscillator circuit.
This unit, weighing a few ounces, would seem to be directly applic-
able to the general aviation aircraft.* The tone transmission
period (for good reception) is only 40 milliseconds. With 40 milli-
seconds between successive tone combinations, any number can be
transmitted in a series. By two consecutive transmissions some
256 (16 X 16) codes are generated. Each code requires 120 milli-
seconds. Three sequential dual tones provide 4,096 codes. The

---

* See Bell Telephone System: Monograph No. 4495, May, 1963.

UPPER GROUP OF TONE FREQUENCIES

		A 1209	B 1336	C 1477	D 1633
V	697	AV 1	BV 2	CV 3	DV 4
W	770	AW 5	BW 6	CW 7	DW 8
X	852	AX 9	BX 10	CX 11	DX 12
Y	941	AY 13	BY 14	CY 15	DY 16

LOWER GROUP OF TONE FREQUENCIES

MILLISECONDS *

ONE DIGIT = 16 CODES

TWO DIGITS = 256 CODES

THREE DIGITS = 4096 CODES
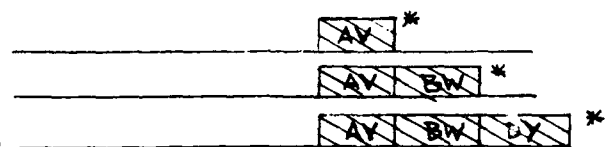
♦ Maximum data rate; add up to 40 milliseconds between digits depending on encoding speed and radio link characteristics.

BELL 4 X 4 DUAL-TONE SIGNALING SYSTEM

FIGURE 15

latter case requires a transmission period of 200 milliseconds by present standards.

Using 4,096 codes for air-to-ground position-identity reporting, fifty general aviation aircraft (if operating on some form of time-shared roll-call system) would require only a single VHF channel. This assumes 10 to 15 second reporting intervals, allowing some "buffer" time intervals between transmissions.

Similarly, the selective calling from the surface (ground-to-air) may be used in a parallel manner to provide 256 or 4,096 addresses, messages, etc. A simple tone system using the existing VHF links can achieve many valuable results for general aviation at very low cost.

1. Multi-Tone Code Structure for Data Transmission

This system seems ideally suited for application to the existing VHF voice channels (or VOR-ILS), since the tones are well within the bandwidth of the communication and navigation units. Years of research at Bell Laboratories were devoted to specific frequencies (tones) to minimize any possible activation by voice frequencies, other tones, and to make the signaling as immune as possible to all forms of interference. The multi-frequency, dual tones with unique combinations result in a great deal of immunity and methods for self-checking the messages' accuracy and validity. These are fully exploited in the tone dialing equipments that are now commercially available.

1-Digit Multi-Frequency Code	2-Digit Multi-Frequency Code	3-Digit Multi-Frequency Code
a. 16 codes	a. 256 codes	a. 4,096 codes
b. Transmitted in 40 milliseconds	b. Transmitted in 120 milliseconds	b. Transmitted in 200 milliseconds
c. Digit simulation immunity	c. Digit simulation immunity	c. Digit simulation immunity
d. Easily automated	d. Easily automated	d. Easily automated
e. Error free	e. Error free	e. Error free
f. Suited to VHF radio	f. Suited to VHF radio	f. Suited to VHF radio
g. Manual or automatic	g. Manual or automatic	g. Manual or automatic
h. Low cost air to ground	h. Low cost air to ground	h. Low cost air to ground
i. Directly compatible with landwire surface net	i. Directly compatible with landwire surface net	i. Directly compatible with landwire surface net

Although one can easily conceive and describe another new data link, it must be recognized that nearly ten years and tens of millions must be spent to achieve the results already obtained by Bell. The real question is: can this fully engineered data transmission system be applied to general aviation for a data transmission system operating at VHF, considering the ramifications of intermittent VHF transmission and the encoding between the data sources and the tone units?

2. Some Examples of Data Transmission

The multi-frequency, dual-tone system described above can be used as a simple manual pushbutton unit for signaling to the ground. Emergency, positional data, altitude data, ATC acknowledgments, etc., typify such air-to-ground signaling. A simple panel of buttons (in fact the one used by the Bell system) would suffice. Data transmission errors are shown to be minimal in such a system as compared with the rotary dial and digital pulse type signals. If, for example, the VOR phase shifter has attached to it a simple encoder with perhaps a signal segment for each 1.5 degrees (this

is ±0.75 degrees, well within the VOR accuracy), 240 codes could be assigned to represent to ATC inputs the specific aircraft's (ground-referenced) positional bearing from the VOR station.

In any one of several schemes the two digit multi-tone signals would be emitted in a short burst (120 milliseconds) from the aircraft. This service would be restricted to only general aviation aircraft (single engine) to avoid overloading the system as airline aircraft will carry more sophisticated and costly equipments. The use of a single VOR station by more than about 25 general aviation aircraft of this class at any one time is remote and thus this capacity seems ample.

The transmission time for the intermittent signals could easily be achieved in less than 0.2 second per aircraft. All aircraft signals (25 of them) could be repeated every 5 seconds. If there is a safety allowance for increased traffic or for another digit (going to 4,096 codes), this still would result in a report about every 8 seconds. Even 20 seconds between reports (3 per minute) may be reasonable considering the low speed of the aircraft and the use of ground units for position smoothing and updating prior to displaying the position to the controllers.

Since the VOR has a voice channel, it could readily emit a simple tone for a two-way DME measurement. The repeat of the DME tone results in the emission from the aircraft also being encoded with its range. This is illustrated in Figures 16 and 17. The multiplexed DME tone transmission can occur simultaneously with the two-digit, dual-tone VOR (air-to-ground) signaling. Thus, both range and angle are reported to the ground station much as the SSR beacon does today. Admittedly, some means would be needed to utilize the aircraft transmitter in this intermittent mode, but it would seem to be a minimal additional cost, once it is engineered. For example, the final stage voltage is keyed on for the 120-millisecond transmission.

This keying can be done by a "listen-in" circuit derived from the voice channel of the VOR itself. For example, as the
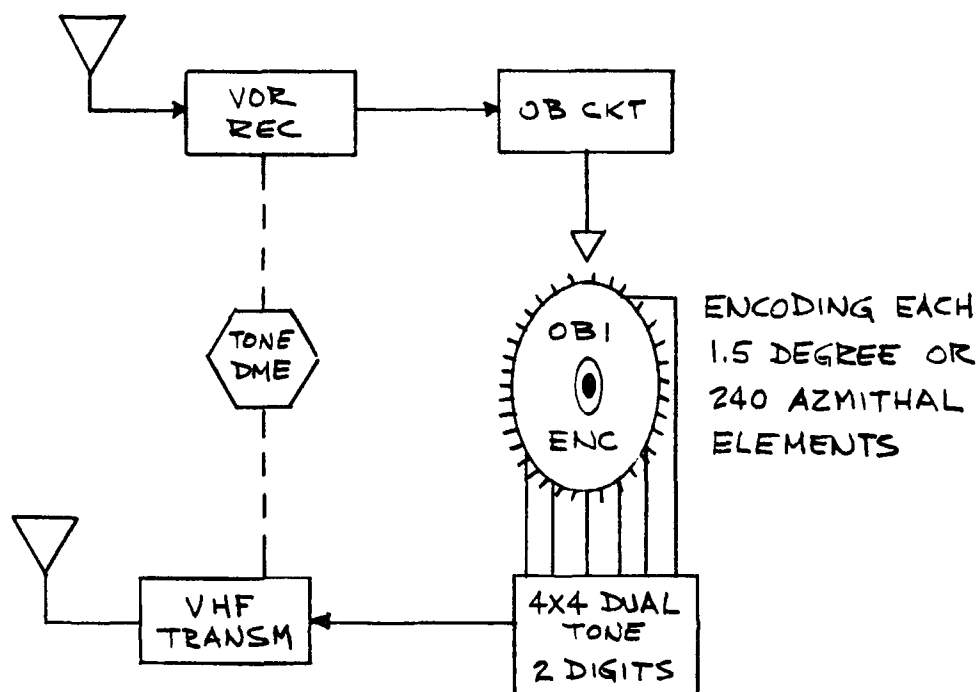
200 millisecond transmission allows 50 aircraft
to report in a time-ordered sequence in 10 seconds.
Multiplexing of tones with Tone-DME modulation
is feasible since the 4 x 4 system is designed
to be immune to other modulation frequencies.

SIMPLIFIED VOR ENCODING USING TWO-DIGIT DUAL-TONE SYSTEM

FIGURE 16

AIRBORNE EQUIPMENT

GROUND EQUIPMENT

200 MILLISECOND AND TRANSM
(OF DME TONE) AND 4 X 4 DATA SIGNAL

TIME SLOT SELECT

(SLOTS 1-50)

4X4

TONE DME

T

30-CPS COUNTER

START SIGNAL

VOR R

DME TONE

R

VOR T

9960 FSK AT To

MOD VOR-30 CPS

TONE OSC

PHASE COMP

200 MILLISECOND TIME SLOTS

AIRCRAFT A

AIRCRAFT B

FSK START

SLOT NUMBER

To

0

31

42

50

10 SECONDS

TIME SLOT ASSIGN 1-50 BY IDENT

AIRCRAFT IDENT

AIRCRAFT DIST

AIRCRAFT AZIMUTH

ATC SYSTEM

A – ATC assigns pilot slot number
B – pilot selects slot
C – Aircraft replies DME tone
D – correlation of tone DME phase
     and time slot provide distance
     and identity
E – "4 x 4" dual-tone, VOR encoding
     adds Azimuth

Trace signal paths 1 to 11 for identity and azimuth
Trace signal paths A to I for range or DME output

TIME-SHARING TONE-DME USING TIME SLOT ASSIGNMENTS

FIGURE 17

52

aircraft take off and are cleared by the tower (even visually) they are given a number from 1 to 25, and this is recorded by the pilot by turning a knob or digital wheel to his assigned number. This number is simply a time slot associated with a given timing reference also emitted on the voice channel of the VOR. It could be the same dual-tone systems in reverse. When the 120-millisecond time slot arrives at the prescribed instant within the overall 10-second interval, the aircraft transmission takes place. This gives the ground receiver and processor both the range and angle of the general aviation aircraft, using little more than the current VHF transmission system. The time slot number or relative time of transmission within the period provides the aircraft identity (Figure 18).

The use of the VHF transmitter unit for voice is still possible, since the immunity of this unique tone-signaling system to voice is one of its greatest virtues, as proven after some years of testing in the laboratory and hundreds of field installations. Admittedly, discipline would have to be maintained on the specific VHF frequency assigned to the VOR-tone DME reporting. Nevertheless, the pilot can quickly switch to a clear (voice-only) channel and back again even within his 10-second "dead-time." Most air-to-ground transmissions last less than 3 to 5 seconds since the civil ATC vocabulary has been so well developed.

A limited amount of monitoring of the New York ATC center (on a non-busy VFR day) using a frequency of 119.8 Mc (Douglaston) indicated the following samples of duration of air-to-ground and ground-to-air voice transmissions:

Air to Ground (seconds)			Ground to Air (seconds)		
1.1	0.6	1.9	4.1	0.6	3.9
2.2	1.1	1.4	2.2	2.0	1.9
1.5	0.8	1.4	2.6	2.2	2.1
3.5	2.1	0.5	3.1	5.5	5.1
1.5	0.7		2.9	1.8	6.5
1.9	1.0		1.2	5.2	1.4
0.9	5.5		3.7	4.9	
0.8	0.4			1.0	1.5
3.4	3.3		0.9	2.6	
				4.9	

AX, BY, ETC. 4X4 DUAL TONES
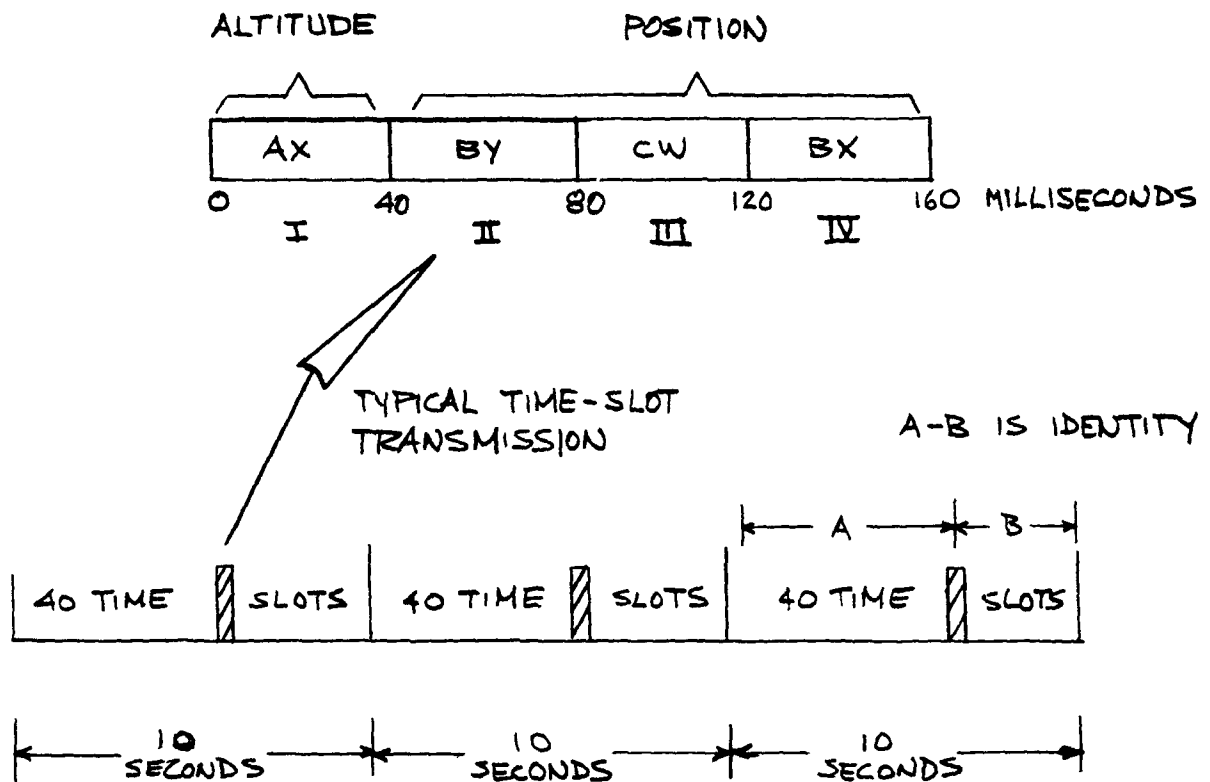
(16)   ALTITUDE   FIRST DIGIT
(4096) POSITION   DIGITS 2, 3, 4
(40)   Identity   Slot assignment in time-ordered roll call.

USE OF DUAL-TONE SIGNALING ON VHF FOR SERVICE TO FORTY AIRCRAFT

FIGURE 18

3. Roll-Call Data Transmission Techniques (Figure 19)

It should be noted that the roll-call technique (the time the aircraft reports and repeats the ground-originated tone DME) can alternatively be programmed by the azimuthal position of the aircraft. For example, the starting period of the transmission would be related to the aircraft's position as follows:

Degrees Bearing from VOR North	Time
0	0
36	1.0 seconds
90	5.0 "
270	7.5 "
288	8.0 "
360	10.0 (cycle completed)

With such a roll-call method, the start time would be transmitted to the aircraft by means of the VOR voice channel or perhaps by an intermittent perturbation of the 9.9-kc VOR subcarrier. Other methods may prove equally suited, such as using the 30-cps AM signal for a timing reference, for the multiplexing of such a simple signal.

This latter signaling method has some attraction for low-cost general aviation application, since it may simplify the usage of the system as angle becomes a linear variable for data processing or display. It is, of course, completely feasible to develop a ground display for presenting this reply signal to an ATC controller, much as a radar display. The processing of the tone signals representing the omni-bearing of the aircraft and its range could be so simple that each tower could have displays of all its localized traffic. The same signals would be passed to the ATC center for relating to other air traffic.

Using the VOR has some advantages and disadvantages for programming the transmission period from the aircraft. The main advantage is that aircraft listening in on the channel can have some appreciation of the relative position of other aircraft in their vicinity. This is a simplified proximity warning signal. The disadvantage is that the channel is used inefficiently, since
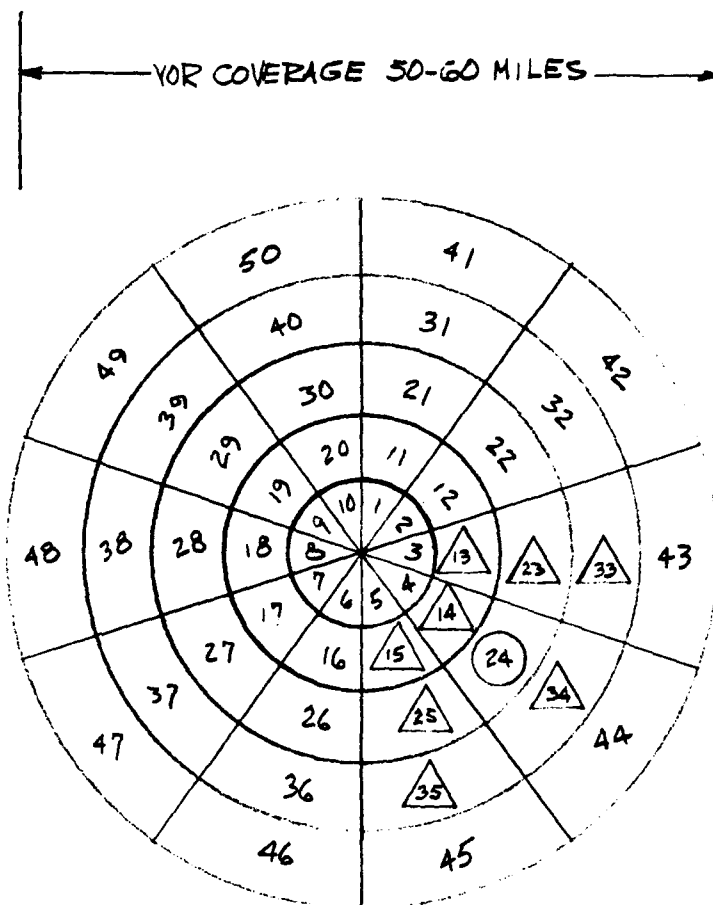
Fifty Tone DME time-slot assignments by combination of VOR and DME positions. Aircraft occupying position "box" 24 is in time slot 24. By "listening-in" to time slots 13, 14, 15, 23, 25, 33, 34, 35, proximity and general direction of a other aircraft is evident to subject aircraft. Simple time-sharing of 50 time slots provides orderly transmission periods of 200 milliseconds for Tones (DME and 4 x 4) and geographic type "roll-call."

AIR-TO-GROUND TRANSMISSION TIME SLOT DETERMINED BY AIRCRAFT POSITION

FIGURE 19

most flight tracks tend to group in certain azimuths of a station for traffic or geographic reasons. Only a thorough analysis can establish the relative merits of the two.

4. <u>Tone Signaling for Differential Omega</u>

The description of the tone-signaling system providing a position report at the ground ATC system using VOR and tone-DME can also be applied to reporting air-derived differential Omega data (Figure 20). The Omega system of course uses two LOP's to completely determine the aircraft's coordinate position, whereas a VOR provides but a single coordinate. Thus, the Omega reporting would be somewhat different as the need for the multiplexed tone-DME (ground originated) could be circumvented. The air-to-ground message might use the full capability of the 4,096 codes (three sequential dual-tones). Numbering the rectangular position "boxes" of a given area in a serial fashion would cause each code to represent a given position. Assuming the Omega position-boxes were 1 mile on the side, and an area 64 miles on the side (64 X 64 miles could be utilized to this accuracy), normal VOR accuracy is greater than 1 mile beyond 20 miles, thus, no degradation of system capacity occurs.

Another potential use of the tone-DME in conjunction with Omega is the resolution of the 8-mile ambiguity that exists with the high-speed or fine grain measurement (only 10.20 kc) signal of Omega. The airborne Omega equipments might thus be simplified, not requiring two to three speeds to resolve the 8-mile ambiguities of Omega. If the report to the ground station could also resolve the ambiguity by the transmission time and direction, this advantage could be gained. Many instantaneous VHF DF's exist that would be adequate. The resolution of the 8-mile ambiguities with range and angle require only the crudest of DF measurements. The tone would be non-ambiguous out to around 100 miles if it were in the 900-cps region (avoiding the dual-tone, digital signaling frequencies). The ground DF (VHF) would need only to be accurate to within 10 degrees or so.
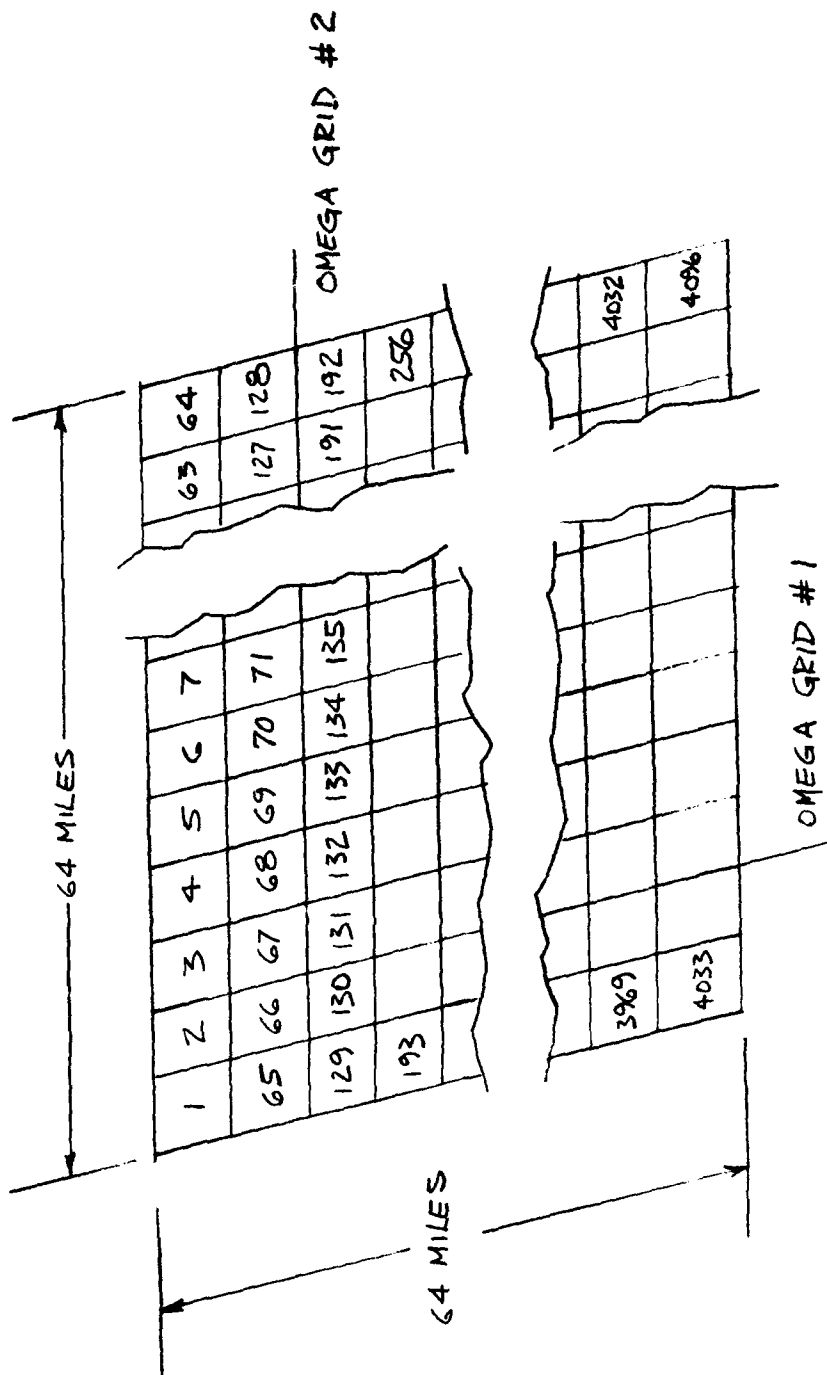
THREE DIGIT DUAL-TONE CODES (200-millisecond transmission time) ASSIGNED
TO A 64 X 64 OMEGA, OBLIQUE-PARALLEL, LATTICE FOR AIR TO GROUND POSITION REPORTING.
AIR-TO-AIR proximity warning is achieved by pilot monitoring VHF channel
conveying these position reports.

FIFTY-AIRCRAFT POSITION REPORTING SCHEME (ONE VHF CHANNEL)

FIGURE 20

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5. Area, Low Altitude Coverage for Aircraft VHF Data Transmission

Communications siting of ground units is so much easier than VOR or VHF-DF siting that to obtain the best low-altitude coverage, perhaps a net of low-power, telephone-pole-mounted VHF units would suffice as the ground "interrogate" and "reception" units. Only simple data not navigational information is radiated so that a dipole is all that is required (Figure 21).

The cost and simplicity of this approach is advantageous if the telephone poles and the dual-tone signaling system are used, Since this approach is compatible with the national phone network, it would minimize the cost of the aircraft owner and the cost of the air traffic authorities. Furthermore, coverage at the lowest heights can be realized, since Omega is good to all heights--in ravines, behind buildings, down valleys, on the ground, etc.

Not to be overlooked with Omega is the potential for the air-sea rescue of downed, small aircraft. Since the Omega receiver unit can be designed to use minimal power (flashlight batteries), the downed aircraft would have a position to report even on the surface or in a valley where VOR or VORTAC signals do not penetrate. The relay of this data by similar battery power VHF to aircraft carrying no special equipment (such as the ARA-25, etc.) by voice or a semi-automated VHF-rescue transmitter would aid greatly. Quickly locating the downed aircraft and crew would be an added advantage. Several recent accidents in general aviation suggest that this attribute of Omega is something the Air-Sea Rescue experts might find of value.

One potential use for the combination of tone-DME, VOR, angle encoding, and the 4 X 4 signaling system is to generate a synthetic ground display of locally controlled general aviation aircraft (Figure 22).

200-MILLISECOND THREE-DIGIT SIGNAL EACH LASTING 10 SECONDS

200-MILLISECOND THREE-DIGIT SIGNAL EACH LASTING 10 SECONDS

CENTRAL DATA PROCESSING OF 4096 CODES USING BELL LAND WIRE AND CENTRAL DECODING

TONES SAME AS BELL SYSTEM

POLE-MOUNTED VHF RECEIVERS CONNECTED TO TELEPHONE OR POWER TRANSMISSION LINES
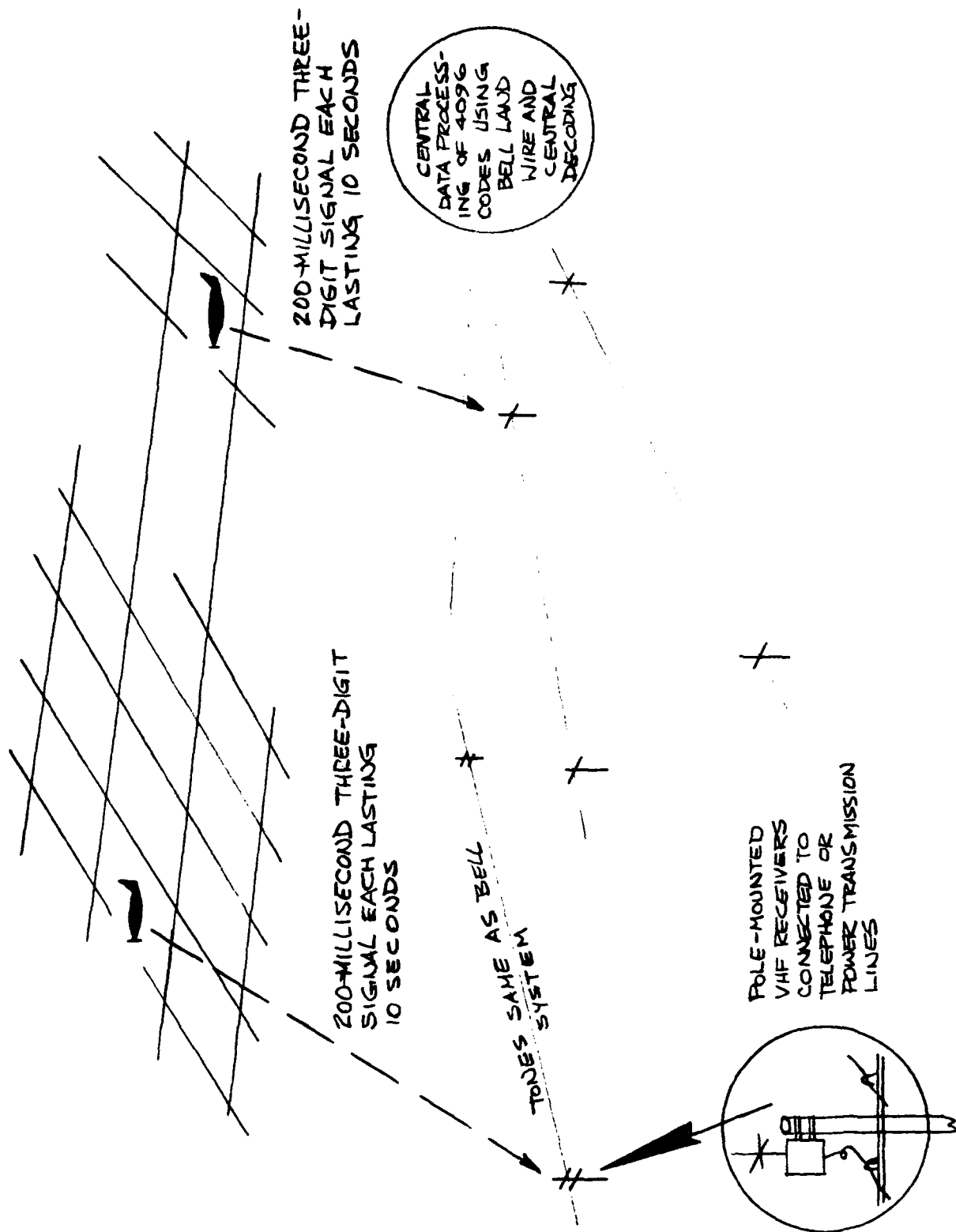
AUTOMATIC POSITION REPORTING USING BELL DUAL-TONE SIGNALING SYSTEM ON NATIONAL BASIS (LOW-COST GENERAL AVIATION AIRCRAFT ONLY)

FIGURE 21

60
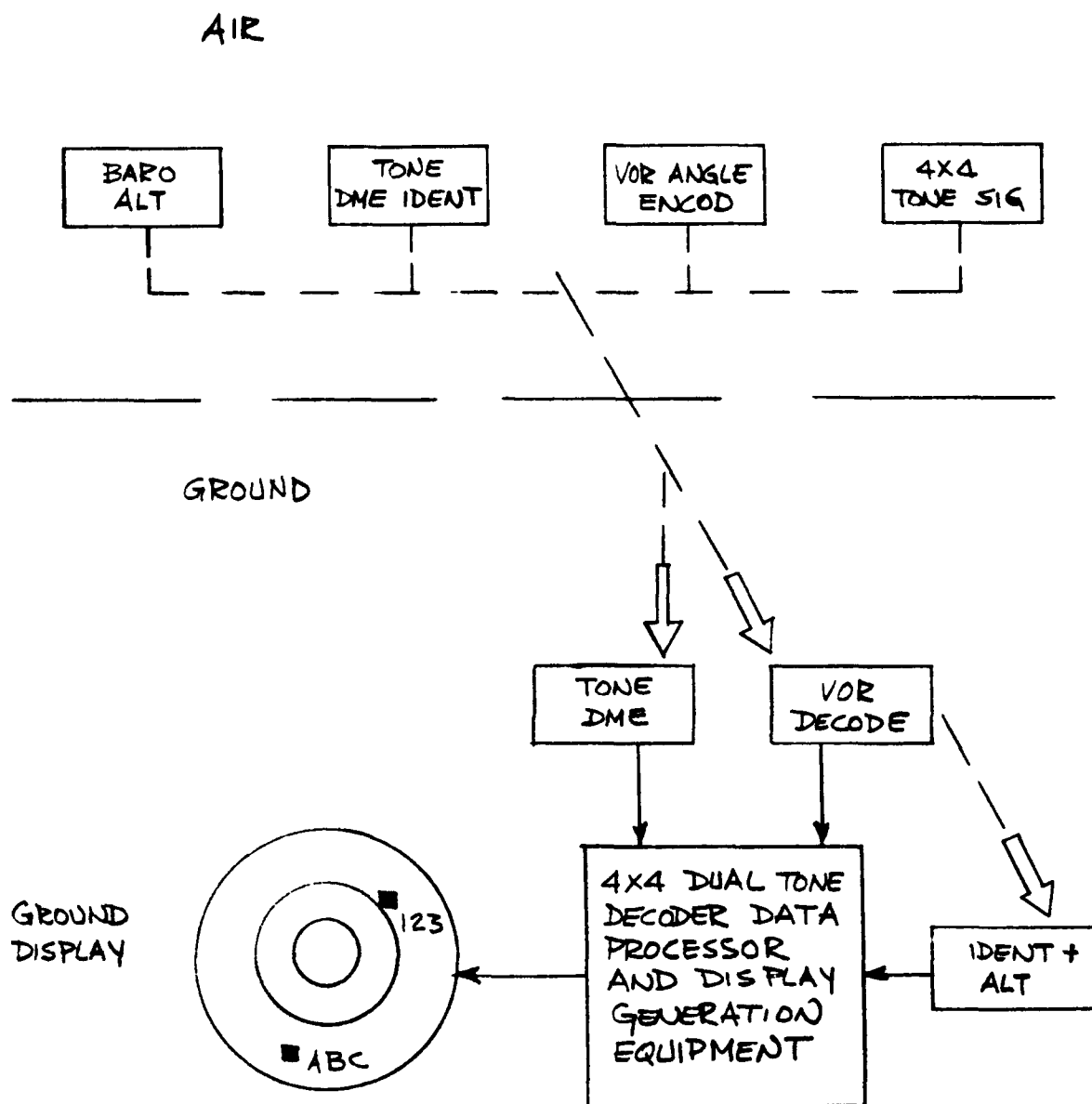
POTENTIAL GROUND DISPLAYS OF GENERAL AVIATION AIRCRAFT
USING VHF, TONE DME, AND BELL TONE SIGNALING

FIGURE 22

III. GENERAL AVIATION USE OF THE NATIONAL SECONDARY SURVEILLANCE RADAR SYSTEM (SSR)

A. GENERAL

Recent projections indicate that the airline fleet will total 3,500 aircraft by 1977 and that the general aviation fleet will total 150,000 aircraft. The current figures (1967) are 2,500 and 95,000 aircraft respectively. The upgrading of the air carrier fleet to nearly 3,000 jet aircraft results in large increases in passenger capacity per aircraft. Average increases of speed and size permit the total number of air carrier passengers to increase four-fold while the fleet size increases only about 40%.

A trend toward increase in size and sophistication of general aviation aircraft is also evident, but they will probably never be able to carry the extremely complex and costly electronics carried by the air carriers. Many business aircraft are well-equipped, but represent only a fraction of general aviation.

The trend toward a nearly full jet fleet of air carriers suggests that, beyond the terminal areas, the typical jet will be at higher altitudes than the typical general aviation aircraft. The more sophisticated business jets, because of their cost and operational nature, can operate and be processed by ATC much as an air carrier because they have a nearly full electronics complement.

Another factor that has a serious impact is that both the air carrier and the general aviation aircraft desire to operate at altitudes less than 10,000 feet and predominantly around 3,000 to 4,000 feet when they are within 40 to 50 miles of the major terminal areas. Transportation economics and other factors encouraging air carrier operation in a given geographical region also encourage the use of general aviation; thus, there is a compounding of the problems in the dense areas such as the Northeast corridor, Chicago-Detroit, and the Sout' 'st corridors. If one were to distribute the traffic more exte. _,ely in height and horizontal position, the job would be much easier. However, aircraft serve the

population centers and thus the concentration of air traffic in these areas will continue to grow as long as no major inhibition to the growth of air carrier or general aviation develops in the coming years.

In general, the collision potential increases geometrically with the increase of users of a common volume of airspace. Similarly, it increases with speed and the associated lack of maneuverability. Consequently, the doubling of general aviation and the 40 to 50% increase in air carriers by the mid 1970's will increase the potential collision risk by a much greater ratio than the mere ratio of increased populations.

The FAA (reference 6) provides an illustration of the routing and altitude congestion due to the convergence in height and horizontal dimensions (Figure 23). The relatively large traffic at altitudes of less than 5,000 feet and greater than 1,000 feet (only 4,000 feet wide) is evident in this survey.

It will be noted that the total airline and general aviation aircraft were 72 and 188 respectively during this instantaneous (all airborne simultaneously) peak of 266 aircraft. This typical mixture of controlled and uncontrolled traffic in VFR will become impossible with the large increases of potential VFR collision that can be projected for 1977 aircraft populations.

Some form of increased discipline will be necessary for the "safe and expeditious" movement of air traffic even in VFR in such areas, and, of course, major improvements in the IFR handling of air traffic will be mandatory. Techniques to aid both IFR and VFR in high-density airspace are required. The efficient flow of traffic is the main objective of the traffic control system. The avoidance of collision is an essential, specific by-product of the air traffic control function, but it is not its only mission. The concept that air traffic control exists in high density areas only to prevent air-to-air collision avoidance is a mistaken concept.

Although two ships have rules they must follow when passing each other, the relative motions of each to the other,

A.—Peak Instant Flight Altitude Distribution by Aircraft Owner, Chicago Terminal Transition Area (90 N.M. Radius) 2319 GMT Friday, August 1961

B. —VFR Traffic Flow Pattern, Chicago Terminal Transition Area (90 N.M. Radius) 4-6 P.M. Friday, August 1961
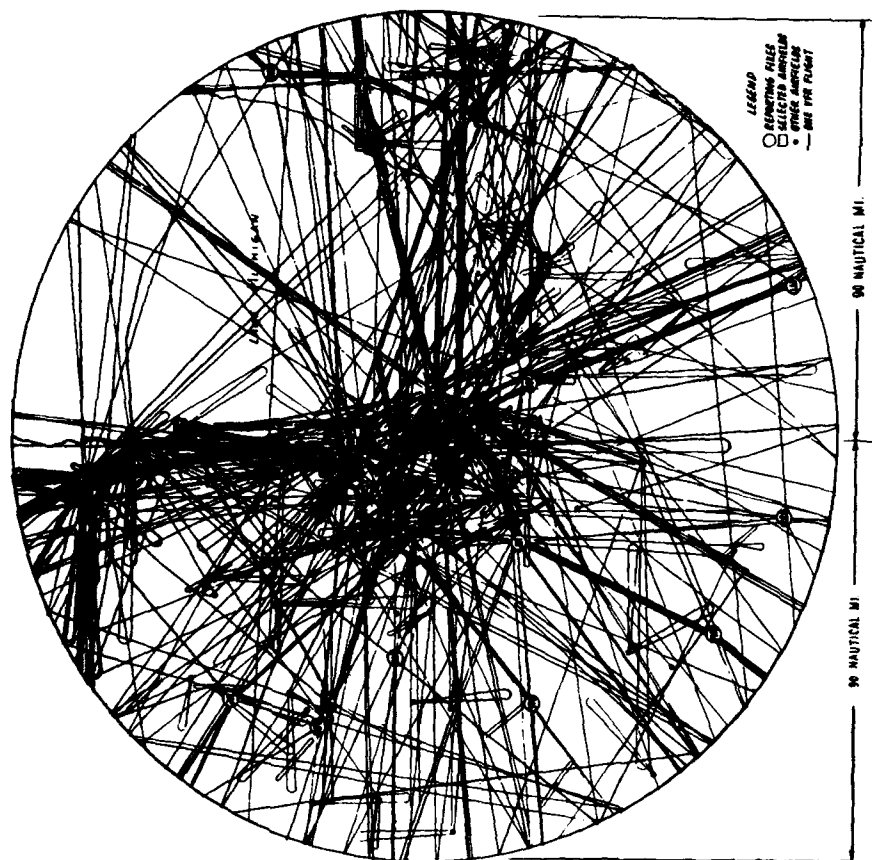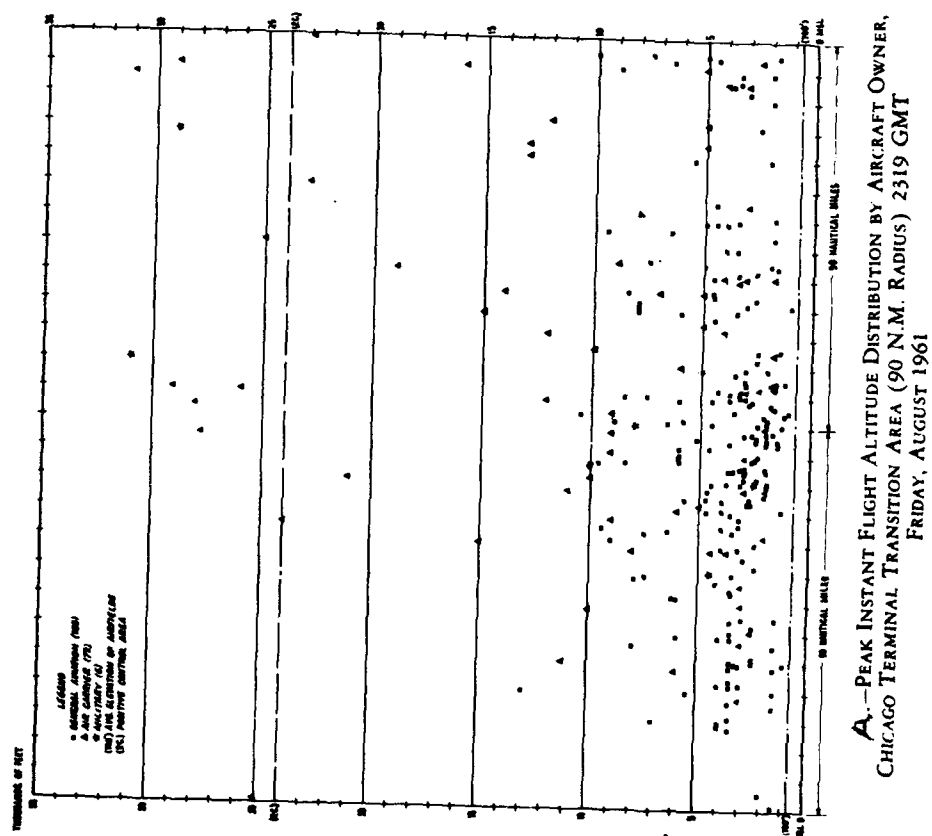
TYPICAL CONCENTRATIONS OF TRAFFIC IN BOTH THE HORIZONTAL AND VERTICAL PLANES (OUT OF 266 AIRCRAFT ALOFT, 188 ARE GENERAL AVIATION AIRCRAFT, AND ABOUT HALF THE TRAFFIC IS AT AN ALTITUDE BETWEEN 2000 AND 5000 FEET)

FIGURE 23

64

without a fixed reference, are hazardous. Inability to relate the two tracks, speeds, and headings to one another because each is in motion results in an increasing loss of shipping in congested waters. The same is true with aircraft. The use of good radar on ships so that they can clearly see each other has, surprisingly, not diminished the number of collisions in tight quarters. In western European rivers there have been 2,000 collisions in the last 5 years, many in VFR (as well as poor visibility), but often with radar functioning in both cases. Each issue of the "Journal of the Institute   ation" discusses the menace to shipping in the most detailed terms. This point is made to bring out that even in the oldest form of vehicular motion the observation of the other vehicle and vehicle traffic control are not always enough. Mariners have yet to find an acceptable solution for simple cases.

For ground control, the Air Traffic Control (ATC) system of the present is rapidly being shifted to function with secondary radar data rather than primary radar data. This is true because the targets are far more discernible on the controller's display and other forms of information (height, identity, etc.) are automatically associated with each target under observation. With the transmission of the aircraft beacon codes, much of the manual correlation of flight plans, re-identification, altitude following, and collision avoidance can be semi-automated by machine—yet retaining human responsibility and monitoring to reduce time of decision and to make the pilot-controller workload under dense IFR traffic conditions tolerable. Signal formats are such that more control automation can be added with experience. For example, in addition to displaying and processing the traffic data at an ATC center with several remoted radar inputs, each terminal of any reasonable size uses its own radar at its own tower for beacon (SSR) and primary radar traffic control.

The system works on the premise of accepting traffic with some biases applied as it becomes busy to safely maximize the use of the airways, runways, and terminal airspace to the greatest extent

possible with today's navigational aids (mostly VORTAC-DME). Each routing, scheduling, and altitude-separated crossing is examined for conflicts in the process of being accepted as a valid flight plan. As the actual traffic subsequently executes the flight path (and plan), its minor variations are carefully noted so that a minimum of conflicts develops. The airspace traffic loading is currently determined primarily by the limits of acceptable runway movements under IFR conditions. Each flight is shifted (delayed) in time when full runway capacity is approached. Often, what appears as airspace limitation is in reality runway capacity and landing limitations. Generally delays are equitably applied and geographically distributed through the system. Those who can respond to changes most readily often get preferred treatment because this is the most efficient way to process delays. Each action is safe in the decision making process and in the pilot-controller control process so that in conception, and partially in reality, a full collision avoidance system exists in the form of data derived from the SSR and primary radar coverage of the country.

B. AIRBORNE COLLISION AVOIDANCE EQUIPMENT

The proliferation of new collision avoidance systems (CAS), proximity warning equipments, etc. (reference 1) indicates that the state of the art is progressing toward an ultimate solution. However, from the current practical viewpoint, the major CAS contenders have incompatible electronic techniques--not even a commonly agreed-to concept exists (simulation of a theoretical system will be completed in 1968). A radio frequency satisfying angular accuracies is unresolved, and several systems that were thought to be adequate have not succeeded when they were reduced to practice. Several years of flight validation, agreement on system specifications, and large production is essential before any realistic value can be placed on these CAS systems. As seen from the reference material (such as reference 4), the SSR system which has top civil and military backing, is only now becoming widely implemented some 10 years

after nearly 95% of the basic criteria of the system were agreed to, flight-validated, and tested in service.

About the most important result to date is the agreement that a cooperative system is needed, meaning others must adhere to a standard. One can deplore the time cycle of cooperative electronic system developments, but they are a fact of life and disillusionment will befall anyone who will not take the time to examine how such major systems are finally brought into being.

Simple, logical, or even political steps leading to an acceptable selection if a basic philosophy or concept must then be followed by such engineering steps as:

1. Choice of one radio frequency (L, X, S, K, or C band are typical)

2. Choice of specific modulation signals (pulses, CW, AM, FM, Doppler, time multiplex, frequency multiplex, etc.)

3. Choice of air and ground antenna systems (static, scanning, lobing, etc.)

4. Data processing (air or ground, computer, pictorial, analog, digital, automatic)

5. Establishment of a "Signals-in-Space" standard

6. Flight validation of prototypes (re-examining steps 1 through 5, executing some changes)

7. Obtain national, international, and civil-military agreement (many systems have failed at this point--particularly cooperative type systems)

8. Ground installations

9. Air carrier installations

10. General aviation and military aircraft installations

11. System now in being may still have limitations or flaws requiring "in-service" fixes (such as ILS, Omni, SSR, etc.) before full reliance is achieved.

Although a major manufacturer, after due consideration of the market and with some preliminary financing, can go from the paper design stage of a new aircraft to operational usage in 5 years, supporting (cooperative) electronic systems require at least 10 years and usually 15 years for full implementation. The aircraft

installation of such cooperative equipment is merely the last of many steps. To be effective, a collision avoidance equipment must be carried by all aircraft, placing stringent emphasis on such a system vs, say, a landing system where even partial implementation is useful.

Thus, it is unlikely that any "breakthrough" in the collision avoidance techniques will be seen that will be adequately agreed to and implemented simultaneously by the big users of the airspace (airlines and general aviation) within a decade. This, however, will not discourage the technological search since the problem is well identified and widely discussed. Experts abound on this problem. The point to be remembered here is that the multi-step process needed to engineer any cooperative electronic system, be it color TV, a new ILS, communications, etc., will take a long period of time. It is a fact reflecting our complex technological society.

The advent of solid-state (great reliability), micro-miniaturization (light weight), and other electronic (state-of-the-art) advances offer many new potentials but have not really shortened the system implementation process. In fact such new advances might lengthen it, since so many competitive concepts are now more realizable than in the past. Furthermore, we are not in the period of 1956 when major mid-air collisions forced White House acceleration of the aviation facility planning. We are removed over 10 years from this stimulus. These 10 years have seen major improvements such as the SSR (Secondary Surveillance Radar System) with alpha-numeric displays for both civil and military aircraft, making the effort to introduce competitive concepts even more difficult. As noted, most experts agree now that collision avoidance will only be solved by cooperative methods. This decision alone is far-reaching, since non-cooperative methods have failed and the planners are willing for the first time to fully face the extent of a coopera-tive air-to-air and air-to-ground system. Such a decision simply makes the multi-step system engineering, planning, decision making, and implementation mandatory. In contrast, an airborne radar does

not have to cooperate with other electronic equipments and can
follow a much shorter development cycle. The steps enumerated or
similar ones must eventually be followed. The road to success is not
easily found nor is it easily followed. Some dozens of ATC, colli-
sion warning, and similar system concepts (and sometimes hardware)
have failed at one of the eleven steps. One case involved the
voluntary cancellation of a 10-million dollar contract.

The history of these failures typifies the need to better
understand the total system engineering job that must be done.
Shifting of personnel, corporate discouragement, and governmental
reorganization in aviation areas are some of the reasons for failure
since continuity of effort is needed for success. Ten to fifteen
years is much longer than the life cycle of these intangible but
important parameters of system engineering.

C. SURVIVAL OF THE SSR SYSTEM AND ITS MODERNIZATION

As a result of the many unsuccessful competitive efforts
(and perhaps expenditures of several hundred millions of dollars
since World War II), the SSR system is the only one that has sur-
vived. It has survived primarily because of its initial start in
the (IFF) military field and because a sufficient basis for conver-
sion to ATC service existed. Furthermore, about seven or eight
serious faults identified in about 1950-1954 were methodically cor-
rected (side-lobe suppression, defruiting, code structure, altitude
transmission equipment, code "garbling," bright displays, alpha-
numerics, radio channel interference, etc.). The earmarks of a
successful system are its "tenacity" to survive technical short-
comings by redesign and/or to survive after failure of other systems.
Each fault was corrected to the point that a workable system sur-
vived, and it is used today by both the military and international
civil users (NATO and similar bodies included). Some 2 to 3 billions
will have been invested since the inception of the system, a third
of this being committed in the last few years (and through 1970).

D. **USE OF THE SSR SYSTEM FOR COLLISION AVOIDANCE**

It is likely that a system that has been proven so versatile and has survived and overcome major faults can probably be the basis for both collision avoidance and air traffic control. Certainly, the development costs to determine this are minimal. The specifications of the system have sufficient latitude to include a form of modified airborne transponder that could be built and installed for so little that any user of a general aviation aircraft would eventually consider this unit as the second electronic equipment (vs VOR) he should purchase--the communications equipment always coming first. It will permit him to fly safely in dense airspace and assure him of avoidance of other aircraft, since the ground surveillance system can be adjusted to see all equipped aircraft. The equipping of all aircraft is the essence of cooperative collision avoidance. This would seem to be the most economical and rapid way of achieving a reasonable population of equipped aircraft.

Nevertheless, it will require haste to realize sufficient installations in general aviation aircraft within a decade. This could hold the collision rate within bounds and prevent what could be the deterioration of general aviation growth that might occur if a solution is not forthcoming that all can agree to...and is low cost for the user.

E. **OTHER LOW-COST ATC COLLISION AVOIDANCE SCHEMES**

In this report, other schemes besides the SSR will be analyzed that involve a simplified position determination system with communications signals, simplified tone DME concepts, etc. These concepts are worthy of investigation, since navigation, low-cost landing, and other services must be provided the general aviation aircraft whose owner cannot afford to carry the approximately 30 receivers and up to 10 transmitters carried by an airline aircraft. He may not achieve the same performance but, in his own environment, it is probable that he can be satisfied and will be

much safer than he is today. The pressure from the airlines who
represent (they believe) the flying public is such as to go toward
more and more costly electronic sophistication. The airlines
justify this inefficient approach, since aircraft costing up to
25 million dollars a piece and carrying 500 passengers can readily
absorb it. A future single fatal accident can be a national tragedy
and could mean financial chaos to the airline involved. Law suits
exceeding 100 million dollars could be involved judging by the
precedents of past court actions. The courts are finding the
government (FAA) and the airlines liable for certain actions that
they were previously not responsible for. This can radically
change the technical, economic, and R and D pictures since a more
positive assurance of safety may be implied.

        This, however, is probably only typical of the general
public's reaction to aviation accidents, since far more citizens
fly today as passengers on the airlines than in general aviation
aircraft. Furthermore, the railroads have reduced service to such
a point that many individuals are now far more dependent on air
transport than ever in the past, and there seems to be no way of
retreating from this posture. This makes collisions, landing acci-
dents, etc., much more intolerable, since it affects (at least
psychologically) many more people than in the past. The citizenry
is involved, and, with its maturing attitude toward aviation, will
demand even greater safety (lack of accidents) and improved relia-
bility. The lengthy cycle for the development of major electronic
improvements to realize this demand will be under pressure. Based
on past experiences with major aviation systems, it is evident
that time is already running out when the 1977 projections are
viewed in the light of what it takes to implement any new coopera-
tive electronic systems for ATC, IFR, landing, collision avoidance,
navigation, etc., because all areas will require improvements. So
much for justifying the need to extract as much as possible from
a system that exists and has growth potential.

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F. SIMPLIFIED BEACON TRANSPONDER FOR GENERAL AVIATION

Currently, most so-called low-cost transponders are selling in the region of 2,000 dollars and comply with the FAA/ICAO standards for the SSR system. The aircraft transponder is composed of a receiver that is tuned to a radiating ground beam. Certain spacings of received pulses are decoded and used to trigger the associated airborne transmitter. The transponder's transmitter then replies with a series of several pulses between two "bracket" pulses that are spaced 20.3 microseconds. The absence or presence of the specific pulses between the bracket pulses provide over 4,000 combinations, each a discrete code. These codes can be selected by the pilot, upon request from the ground control, so that the aircraft is uniquely identified with its assigned codes. Furthermore, by interlacing (time-sharing) the transponder in the aircraft, barometrically derived altitude can be transmitted using the same codes. If the ground system uses alternately different spacings on the "interrogate" path to the aircraft, both identity and altitude are transmitted in one rotation of the narrow ground beam.

From the viewpoint of the airborne equipment, the receiver can be basically simple with a full solid-state design. The rf power transmitting element of the transponder is the current limitation on the possibility of achieving a full solid-state transponder. This element is being studied by various parties (references 10, 11, and 12) and, because of its wide application, will receive continued, aggressive support.

The 1961 FAA "Beacon" report encouraging a large-scale national effort on the SSR system assumed that a $500 beacon could be manufactured. Time has shown that this is not likely unless some means to reduce costs can be found. To reduce the cost of the transponder and still retain system compatability, the following steps (separately or combined) are possibilities:

1. Use only the two pulse bracket and identification codes.
2. Design a low-power transmitter using a simple solid-state element.

3. Minimize deep nulls in aircraft coverage diagram.

4. Minimize deep nulls and use "height-gain" in ground antenna installations.

5. Reduce transponder controls to a simple on-off function with an ident or "squawk" button (eliminating full coding and complex code setting controls).

6. Examine ground environment processing to determine acceptance of certain traffic levels using the simplified beacon transponder.

7. Consider a 40-mile service range for small general aviation aircraft instead of the current 200-mile range.

8. Use of bracket and ident pulses only.

9. Use broad pulses with less stringent criteria such as those specified by ICAO-Annex 10 for DME.

These possibilities offer large potential cost savings in several ways. The currently specified ability to transmit a burst of up to 14 pulses at a power level of 500 watts within 20.3 microseconds of time requires an "average" power level capacity of transmitter and power supply to avoid power "sag." This is considerably in excess of needs for only two widely spaced pulses at lower power. The utilization of only the two bracket pulses (spaced 20.3 microseconds) and the use of a third pulse for identification (spaced 24.65 microseconds) offers the designer several alternatives in economical transmitter design. Sustaining a specified full power level for each successive pulse in a closely spaced train of pulses requires far more capacity than for two or three widely spaced pulses. Each design should have several economies over a design that is required to provide the full (1.45-microsecond spacing) emission of a long train of pulses. Slower rise times would also be beneficial.

G. LOW-POWER TRANSPONDER

The normal transponder radiates a signal of about 500 watts peak power (ICAO permits the level to vary from 21 db to 27 db above 1 watt). It is possible under many circumstances that are acceptable to general aviation to achieve a very useful SSR service

area with considerably less power. The lower power (about 5 watts of peak power) would permit several additional low-cost features. Some limitations on recovery time, number of replies per unit time from multiple interrogators, etc., would also aid.

To achieve the practical use of low power, several factors must be considered. Some of them admittedly will reduce the performance of the transponder relative to a full-powered airline-type transponder; yet, because of the need to include as many general aviation aircraft into the National Airspace Utilization System (particularly the SSR data processing) as possible, this solution has a much lower total cost and an excellent cost/benefit ratio.

These compromises might be fully acceptable to general aviation light aircraft and the FAA, yet would not be satisfactory to the airlines, because of their different requirements of height, speed, and maximum range. Their equipments would thus remain more sophisticated yet the service would not be degraded by the low-cost units. We will later discuss some of the operational and ground environmental problems that must be considered with this concept. No attempt will be made here to explore the technical details of low-power low-cost solid-state developments. References 9, 10, 11 and many other works describe the state of the art. Needless to say, the rate of progress and results to date indicate that such a unit will soon be or is already in existence. A wide range of other applications is encouraging the development of solid-state transmitters in the power and frequency range needed for transponder applications.

H. MINIMIZATION OF DEEP NULLS IN AIRCRAFT COVERAGE DIAGRAM

Figure 24, which was taken from an early CAA report, illustrates some of the nature of the typical nulls in an aircraft coverage diagram for receiving and transmitting in the L-band region. It should be noted that these patterns were taken with transponder installed in a DC-3 (from reference 4). It can be seen by studying the horizontal and vertical coverage diagrams, that it is most

LEGEND

0 TO +4 db
0 TO -4 db
-4 TO -8 db
-8 TO -12 db
<-12 db

db   Maximum
Power Radiated
at 0° Azimuth
(Nose of Aircraft)

θ   Vertical
Angle, 90°
Being
Horizontal

(A) Contour Map

Scale Factor: 1'24
Model Frequency: 24 KM.C
Pattern: θ = 95°, φ = Variable
Polarization Eθ
Curve Plotted in: Voltage

φ = 0°

Antenna Type: λ/4 Stub
Antenna Location: Belly
Distance from Illuminating Source: 900 feet

(B) Polar Plot
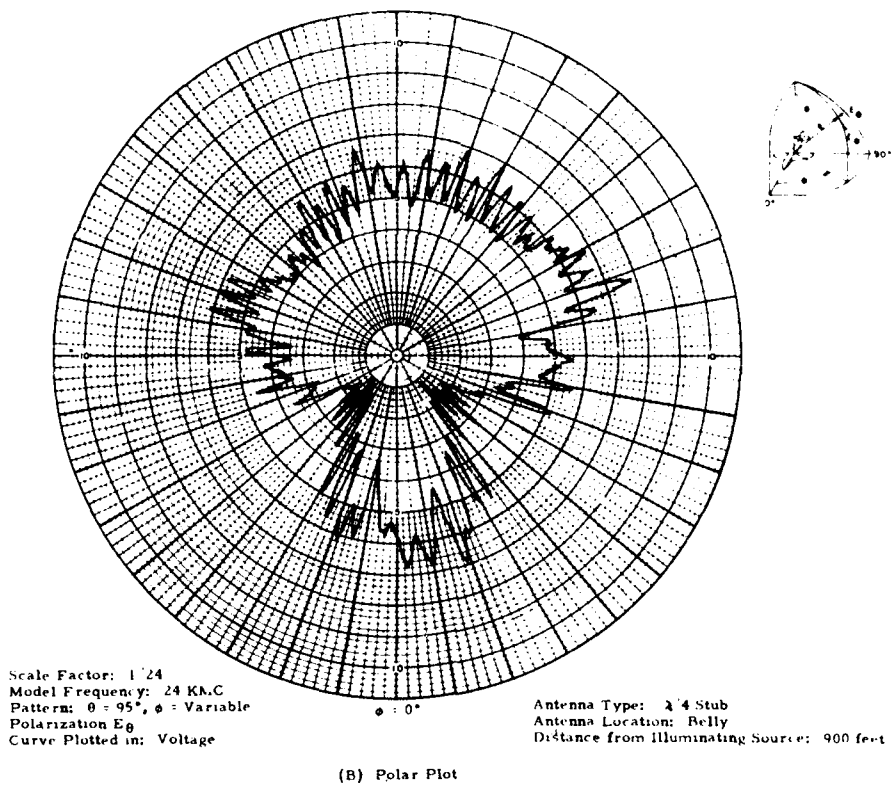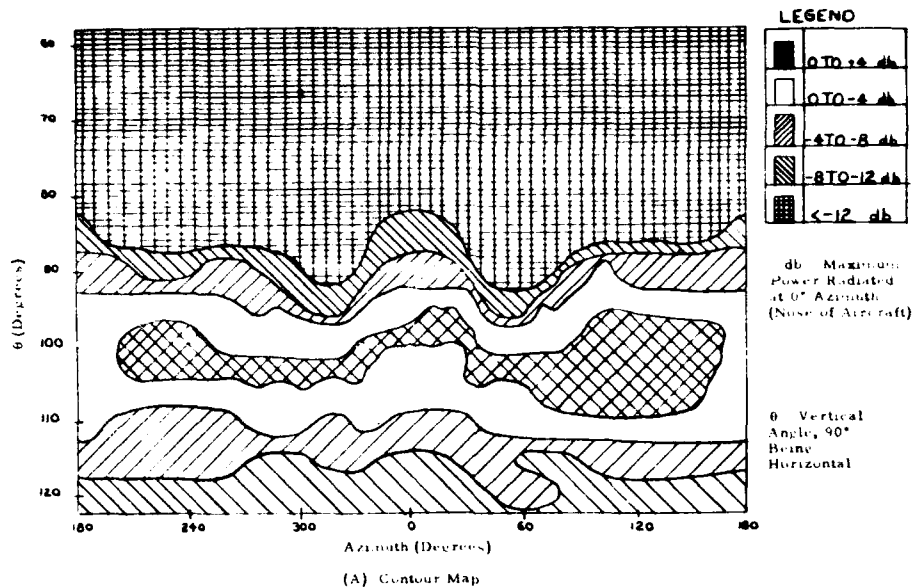
RADIATION PATTERN OF λ/4 ANTENNA ON BELLY ON CENTERLINE OF WINGS OF A DC-3

FIGURE 24

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difficult to obtain even hemispherical coverage without some deep nulls. Bottom-mounted antennas and top-mounted antennas each tend to have a masking effect due to the wings and main body of the aircraft.

It is evident that if a light aircraft with a belly-mounted antenna should bank 40 degrees in a turn that (with single antenna) the signal path could be degraded up to 20 db in the worst case and easily 12 db. The cost of the L-band (vertical polarization) blades is quite low--about $20 to $30. Thus, if a simplified use of two antennas could be established to reduce the "holes" in the coverage diagram far more consistent tracking could be achieved and certainly lower power can be used. A 20-db "hole" due to aircraft attitude (banking, track, heading, etc.) in the direction of the ground interrogation causes the return signal to appear as one that is reduced 100 times in power. A 500-watt signal is then equivalent to a 5-watt signal. Thus, system-wise the 500-watt power level in the aircraft transponder is often used to fill the holes in the radiation pattern and, of course, to establish maximum tracking range at 200 NM. Airline operations at over the 30,000-foot level create large line-of-sight conditions that require large signal strengths. For example, a transatlantic jet airliner arriving off the coast and entering the ATC coverage at 35,000 to 40,000 feet might have a signal path of over 200 miles. This range capability is useful in ATC for spacing trans-ocean departures and arrivals.

However, it is reasonable to limit the medium- and low-cost general aviation aircraft to less SSR service range because their missions are different. This would justify 12 db less power (16 to 1) for this reason alone. Improving the coverage diagram of the ground interrogators with elevated antennas (with greater directivity in the vertical plane to aid the small aircraft) will also aid greatly. This would encourage general aviation to cooperate with a simplified, low-power transponder, providing a means of achieving considerable ATC service improvement with no degradation of service to the other aircraft in the system. Each of these

points will be covered in separate discussions, but we can state here that the relationship of the 500-watt to the 5-watt transmitter (20 db) can be readily rationalized. With low-cost dual aircraft antennas, elevated interrogators in some sites, and increased vertical gain in the interrogator antennas and receiver input, it is possible to readily show an improvement of 20 to 30 db in the signal path, allowing nearly the same performance to be realized from a very-low-power general aviation transponder with only bracket and identification pulses (see Appendix).

I. REDUCTION OF BEACON COMPLEXITY

With the removal of the full coding (1.45-microsecond spacing), the transponder is simplified, since the power supply is less powerful, the modulator is simpler, and the transmitter output stage is simplified (does not have to sustain a continuous—non-sag—high-power burst of 15 to 20 pulses). The cabling and Beacon* control head is another complexity that can be eliminated, further simplifying the installation of the resultant smaller, light-weight unit. The elimination of costly delay lines with many precision taps, the digital code setting control heads, etc., are all appreciable savings. The beacon unit could be reduced to a single package and mounted on or very near the aircraft antenna input. This has the further advantage of good transfer of power into the antenna, sometimes saving 3 to 6 db alone over lengthy cabling and poor fittings. Coax fittings with poor or corroded connections are also minimized.

Thus, by following the route of overall simplification of the airborne unit, the complexities that have a way of compounding the cost and reducing the reliability can be minimized. This may result in a unit that may cost a quarter of the cost of the current units (500 vs 2,000 dollars).

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* Beacon and transponder are used interchangeably here.

J. EFFECT OF GROUND ENVIRONMENT ON TRANSPONDER AND EFFECT OF SIMPLIFIED LOW-POWER TRANSPONDER ON GROUND ENVIRONMENT

The mutual compatability of the simplified, low-power transponder on the FAA National Airspace Utilization System environment is important for the successful application of the idea. The following factors determine this compatability:

1. Ground system data processing

2. Percentage of targets that would have minimum transponders

3. Ground (interrogator) receiver and antenna gains

4. Effect of the side-lobe suppression system on low-power beacon performance

5. The level of interrogation before service is denied, dead time, overload, etc., to minimize airborne power and duty cycle

6. Determination of the number of usable returns from each SSR interrogator rotation period (usually only 10 to 15 hits per beamwidth)

7. Effect of an elevated interrogator antenna to achieve height gain as well as absolute gain of interrogator to transponder signal path. Reduction of vertical lobes with gain and height

8. Possibility of introducing a separate reply pulse transmission and/or reply frequency to reduce pulse traffic loading in the reply channel.

Implementation of point 8 could greatly enhance service to the low cost users. Since the greatest growth in the future traffic (the number of airborne units) is in general aviation, an independent reply channel may considerably upgrade the overall SSR system performance. Yet, no change would be needed in the normal existing, reply, ground processing, and display elements of the system.

Several of these generalized system parameters must obviously be investigated in more detail than is possible here. A study of these parameters could be readily instituted using some of the mathematical modeling of pulse densities used in the past for the SSR system evaluations (references 5 and 8). Fortunately, the cost to experimentally try the concept (actually fly experimental units) would be minimal. The low power level could be achieved

with a normal transponder or DME using power attenuation. The dual antenna installation could be mechanically synthesized in the aircraft and video tapes made of the output of the SSR ground processor to establish the signal levels of target tracking. The use of broad pulses would also be studied. The modifications to the system are such that it would not jeopardize its functioning with the fully equipped aircraft (its overall performance might even be improved by using simplified codes and independent but compatible channels for general aviation).

Such steps would encourage the cooperation of the light aircraft to utilize the great target enhancement achieved with the SSR system and minimize the hazards to airline and general aviation alike. An air-to-air collision avoidance project is underway in the FAA for North Atlantic traffic using the transponders. If an independent interrogate frequency were introduced into the SSR system by this means, the possibility of the air-to-air measurement in large aircraft of the relative position of other large aircraft could be achieved, as has been proposed by several of the collision avoidance systems.

The subjects of ATC and collision avoidance are, of course, inseparable. If the light aircraft could carry a minimum beacon whose signals could be used by the ground processing system of the SSR, much can be done because all targets are tracked in angle and range, and manual insertion of altitude and identification would follow the general aviation target. If the traffic were all equipped with at least the minimum beacon transponder, and all aircraft above a certain level (weight or cost) used the full code structure for identity and altitude, nearly all of the SSR system (which cost several hundreds of millions and required 10 years to install) could be used. The possibility of bringing any of the currently proposed independent systems for collision avoidance up to full level of utilization-- including the "little guy"--is very doubtful for at least another decade.

If the SSR system did not exist, there might be more justification for a CAS system. However, if a low-cost, simplified SSR transponder meeting the signals-in-space minimum standards will satisfy the requirements through ground processing or air processing in the larger aircraft, there is hope that this function can be introduced sooner into the National Airspace Utilization System.

Furthermore, as the smaller aircraft in the general aviation category use more IFR equipments, the desire to have some form of radar control at general aviation and low density city airports is obvious. The SSR interrogator (low power) is much smaller and costs considerably less than a primary (skin return) radar such as the ASR 4 or 5 types. These radars are prohibitive in cost (initial, installation, and maintenance) for other than major air terminals. Although the nation might use 100 to 200 such terminal radars, the hundreds of potential small fields needing some form of improved local tower IFR-VFR control by the 1970-1980 era must be considered. The military, for example, use the SSR in lightweight, portable man-pack units to obtain track data on friendly aircraft. The cost of such a minimum ground installation would be a small fraction of an ASR-5 unit. Circular polarization, large antennas, high power, several MTI units, etc., typifying a primary radar (skin track) are avoided with cooperative radar. No ground clutter or weather return exists in such an installation, and targets can be electronically identified; thus, the system can be more readily used by skilled controllers. Several military projects that use the military version of the civil SSR indicate that the techniques needed for this application are feasible.

K. TOTAL SYSTEM VIEW OF LOW-COST LOW-POWER TRANSPONDERS

By using simplified codes, broad pulses, low power, some improved aircraft antennas and more vertical gain in the ground antenna and receiver, the potential is high for achieving a successful

(very) low-cost transponder. Many individual steps may be needed
before a successful conclusion is reached; however, the implications
that as many as 50,000 to 100,000 light and medium-sized general
aviation aircraft owners might be induced to install and use such
units is very challenging. The dollar value of this market should
interest manufacturers to attempt the engineering of such a low-cost
unit particularly if development funds from a government source
were offered to "prime the pump." At $500 each, a market of 100,000
units by 1975 is 50 million dollars—well worth some consideration
by several manufacturers.

The signal path for the proposed low-cost transponder
from the ground interrogator to its antenna, propagation to the air-
craft antenna and its receiver, and similar elements in the complete
return path add up to the same path gains and losses as today. Air-
craft antenna lobing and lack of vertical directivity on the ground
account for system losses that are often in excess of 20 db.

Tables I and II give typical examples of the path gain
and losses to and from the aircraft. The lower half of each table
indicates the gain and losses on the two paths, assuming a 50-mile
range and certain improvements that should not impair system perform-
ance. The path gains to the aircraft for the low-cost unit certainly
indicate that the aircraft receiver is one area where cost reduction
could occur. By increasing the ground interrogator vertical antenna
directivity by about 8.5 db and by the use of a newly designed antenna
on the aircraft we achieve improved performance by minimizing deep
nulls in both the air and ground patterns. This could result in more
solid tracking and fewer losses of signal when the aircraft is maneuv-
ering, which is very important in terminal areas. With the power
of the airborne transmitter reduced by about 20 db, this must be com-
pensated for by aircraft antenna improvements, reduced range require-
ments, and increased ground antenna and receiver gains. The concept
of "height-gain" in addition to vertical ground antenna gain (azimuth
is already adequate) would do much to reduce the first and second
deep nulls. This is very important to general aviation aircraft
that use these low angle areas.

TABLE I

Air-to-Ground (SSR) Standardized Gain and Losses (references 3 and 4)

ATC transponder output power (500 watts)	57	dbm
Aircraft transmission line loss	-3	db
Aircraft antenna gain	0	
Space attenuation for 200 miles (1090 Mc)	-144.6	db
Ground antenna gain (interrogator antenna)	+21.5	db
Antenna transmission line and filter loss	-2	db
Half power signal presentation	-3	db
Signal to ground interrogator receiver input	-74.1	dbm

A receiver with a sensitivity of -74 dbm will receive a signal with a S/N ratio of about 4 between the half-power points of the beam as it rotates. Lobing (ground) can add 6 db to this figure or reduce it by as much as 20 db, depending upon the aircraft position relative to the vertical lobe structure.

Suggested General Aviation Low-Power Transponder Program (Gains and Losses)

Low-Cost Transponder:

Airborne transponder power output (5 watts)	37	dbm
Aircraft transmission line loss	-3	db
Aircraft antenna gain (better location, possibly two)	+3	db
Space attenuation for 50 miles (1090 Mc)	-132.6	db
Ground antenna gain (8.5 feet vertical gain added)	+30	db
Antenna transmission line and filter loss	-2	db
Parametric amplifier gain or similar improvement to ground receiver front end	+15	db
Half-power signal presentation	-3	db
Signal to (normal) interrogator receiver input	-55.6	dbm

This infers that the aircraft is at a distance of 50 miles and that the 5-watt signal and the other transmission gains added to the SSR system will supply a signal of about -56 dbm or about 18 db greater than in the case of the standardized table above. The additional 18 db can be used in several ways. The cost or complexity of any unit can be reduced or the total airborne power reduced further.

TABLE II

Standard Ground-to-Air SSR Path Gains and Losses

Interrogator output power (1,000 watts)	60.0 dbm
Transmitter line loss	-1.5 db
18-foot antenna gain	21.5 db
Antenna filter loss	-0.5 db
Reduction of antenna gain to half-power point	-3.0 db
Space attenuation for 200 miles (1030 Mc)	-144.1 db
Aircraft antenna gain	0
Aircraft transmission loss	-3.0 db
Required transponder receiver sensitivity	-70.6 dbm

Suggested Ground-to-Air SSR Path for General Aviation Gains and Losses

Interrogator output power (1,000 watts)	60.0 dbm
Transmitter line loss	-1.5 db
Improved ground antenna (vertical gain, etc.)	30.0 db
Antenna filter losses	-0.5 db
Reduction of antenna gain to half-power point	-3.0 db
Space attenuation for 50 miles (1030 Mc)	-132.1 db
Aircraft antenna gain	3.0 db
Aircraft transmission losses	-3.0 db
Required transponder receiver sensitivity	-47.1 dbm

This table infers that by reducing the range to 50 miles and adding some antenna gains, the receiver sensitivity does not have to be as great as in the "standardized" case by over 20 db.

By comparing this data with that of Table I, it is seen that the aircraft receiver normally does not require the same sensitivity as the ground system because the path gains are greater for the ground-to-air path. This additional 20 db can be used in lower receiver sensitivity, which will reduce this part of the general aviation transponder cost along with the reduced transmitter costs given in Table I. Several other possibilities exist in using these gain-loss units in the system design. Reduced range and minimization of air and ground lobing could readily use the additional 20 db, giving more assured tracking of light aircraft.

L. SYSTEM ALTERNATIVES

One must always keep in mind that if we cannot encourage the development and use of such a $500 item, the pilot will use nothing. In this case the ATC system (ground-primary radar) is forced to attempt to "see" the target without cooperation. The signal is in microwatts being reflected from a small aircraft to the ground rather than 5 watts as proposed in the low-cost transponder. Furthermore, the aircraft and ATC will have no means for multi-target identification. The identification function is important, because it complements the efficiency of VHF communications. What may not be recognized is that the national cost to realistically protect others from the unequipped (non-transponder) aircraft is apt to cost additional hundreds of millions. The best of primary radar must be used with powers in the region of several megawatts. The best type of video processing must be used to eliminate ground clutter, special MTI equipment must be used to minimize blind speeds, and circular polarization must be used to reduce rain and cloud backscatter.

The range on small targets at low altitudes (because of siting criteria) is so small that to obtain reasonable coverage the number of skin track units (primary radars) per geographical area must be increased 2 to 3 times to obtain adequate coverage. This is equivalent to the costly low altitude "gap fillers" used in air defense perimeters where the enemy will obviously not cooperate. Encouragement of every sort should be given to transponder use since, with a cooperative target, the ability to observe a Piper Cub is equivalent to that of observing a jet transport. The ability of even a small aircraft to bring down a transport filled with hundreds of passengers is a proven fact.

Merely to discriminate more by regulation against the light aircraft owner is unproductive, since the owners often have (from their point of view) large investments in their aircraft (averaging about 15,000 to 25,000 dollars) and are obviously anxious to obtain more utility than Sunday afternoon VFR flying.

Those who can afford to install equipment that can handle the full beacon power and codes and altitude reporting should be

encouraged in every way to do so. However, the large body of inter-mediate and low-cost general aviation aircraft (about 50,000 to 75,000 by 1975) are reluctant to do so because of the equipment costs and the installation problems. The "kit-type" installation with the no-coded control head equipment and the microminiaturized single unit, mounted next to one of the improved aircraft antennas, would encourage this use. For example, the military missile beacons are often simple units with only a two-wire power connection and a coax fitting for the RF. Otherwise they are unattended and have no other control units. It, therefore, would seem to the govern-ment's best interests from a cost/benefits viewpoint to encourage the development of the very-low-cost transponder by encouraging competitive programs on techniques, antennas, and systems studies.

The general aviation pilot would in turn be "accepted into the system" on an equal footing. To explain what is meant by the latter phrase one must recognize that with poor tracking of ATC radar targets, and no positive means of target identification, the routing must sometimes be quite circuitous. The ability to control "positively" the unequipped aircraft in proximity of the equipped (SSR) aircraft is usually reduced. Consequently, greater separations are often used for such mixed traffic, the unequipped not always obtaining the most efficient service. Furthermore, as the traffic densities grow, the problem of initially obtaining and then retain-ing identity goes up more or less geometrically. This infers that square, cloverleaf, and other types of identification turns, which are wasteful of time and airspace, will be needed more and more if identification is to be retained. A single two-pulse identification code would achieve this for general aviation aircraft.

The above factors often make the flyer of a lower-cost IFR aircraft feel he is being discriminated against. The lengthening of routings, flights over coastal waters in the middle of winter, and the inability to be "seen" by the ATC system at all times with the primary radar in any weather conditions are typical today when

only half of the aircraft are flying that are expected to fly in 1977. Full compliance with the older methods of control is essential--flying the Victor airways and communications with the controller at each fix for identity. In the meantime, it is evident to the pilot, by listening on the simplex channels used for ATC, that others are getting far more expeditious treatment. There is little wonder, therefore, why the "little guy" or private pilot owner often feels left out of the modernized ATC system and is increasingly aware of this feeling as the number of airborne transponders in more costly aircraft increases. He will also be aware that, as the ground environment improves with alphanumeric displays of identity and automatic altitude reporting, he is further removed from ATC coordination without a transponder.

M. SUGGESTED PROGRAMS FOR ACHIEVING A VERY-LOW-COST TRANSPONDER

The following program is proposed to achieve a very-low-cost transponder:

1. Award of development contracts to encourage the engineering needed to apply some of the recent solid-state and microminiaturization techniques. The military "AIMS" project has made progress in this direction, and now may be the time for low-cost spin-offs. Many technical possibilities to simplify a general aviation transponder exist and should be validated.

2. Competitive development contracts should be let for a low-cost aircraft antenna that has some vertical gain and possibly a top-bottom simplified dual antenna scheme.

3. A system analysis should be undertaken on how to obtain improved vertical ground antenna gains, height gains (elevated above terrain), and improved sensitivities of the interrogator (ground) receivers. The improvements in the receiver sensitivity and the effect on high density higher-powered signals also need study.

4. The use of a separate reply frequency should be tested for the general aviation aircraft with simplified broad-pulse transponders. This would permit enhancement of the targets, since interference from other high-powered aircraft transponders would be eliminated and some laxity of pulse-coded replies would reduce the transponder cost (the requirement for a rise time of less than 0.1 microsecond could be relaxed). This can be achieved in the

system by the addition of a single additional receiver. Use of a parametrical amplifier would add an additional 10 to 15 db.

5. Many of the above suggestions can be laboratory tested and then flight-validated in the New York or Boston areas where the SSR ground processing equipment is implemented. The lower-power aircraft transponder and the use of a separate reply channel and broad pulses can be readily synthesized by use of a Tacan airborne unit modified for this purpose. Similarly, the aircraft antennas and a top-bottom switching or passing scheme of various complexities is inexpensive to test.

6. Vertical antenna gain (interrogator) can be measured and tested on certain ground units such as an FRS-8 or ARSR UMT, providing gain over the standard line fed array.

N. SYSTEM GAINS

With the system gains (Tables I and II) calculated for a coverage of 200 miles, the use of the SSR system at lesser ranges, say 50 miles, would provide a 12-db advantage. The use of a vertically stacked and/or two-element antenna on the aircraft could add another 3 db and reduce the aircraft lobing effect. The addition of a 10-db vertical gain which would minimize ground lobes and add gain on both the interrogate and reply paths, and finally a parametric amplifier for the ground receiver would more than compensate for the 20-db reduction in aircraft transmitter power. Tables I and II generally list standard gain-loss figures for the two paths between the aircraft and the ground. Figures are also given for an airborne transmitter with 20 db less power (5 watts instead of 500) for comparison purposes. Obviously, the greatest attention should be given to the air-to-ground or reply path. The possibility of a separate reply channel for the very low cost unit (limited for aircraft under a certain price or gross weight) offers several possibilities. This would suggest that if a separate reply channel is used, pulses should have appropriate spacings (20.3 and 24.65 microseconds) but less steep rise times. The ICAO specifications call for a rise time of about 0.1 microsecond. However, it is possible with a small degradation of positioning accuracy that this rise time could be

changed to a shaped pulse such as the DME pulse with a tapered rise time of about 2.5 microseconds. (See ICAO Annex 10, Parts 3.8.4.6 and 3.5.3.1.3.) This offers the potential use of less critical airborne transmitter components.

The reply channel would now require much less bandwidth (inversely proportional to pulse rise time). As in the DME, the air-to-ground transmission of the low-cost beacon signal could be restrained to a bandwidth of about 1 to 2 Mc (DME is 1 Mc), so that one edge of the bandwidth now allocated for the SSR transponder (about 10 to 15 Mc) could be used. The only additional unit would be a multiplexed narrow-band ground receiver tuned to the band's edge (near 1084 or 1093 Mc). Furthermore, the narrower bandwidth of the receiver (not calculated above) would offer an additional 6 to 10 db of system gain depending on the trade-off of frequency stability and pulse rise time. Low-cost DME (airborne) units seem to be frequency and spectrum controlled within 1 Mc, which is only 1 part in 1,000; this is easy to achieve by today's standards. It is probable that even with the lowest-cost cavity or transmission line (for airborne signals) stabilization, an accuracy of 1 part in 10^4 or 10^5 can be realized so that there would be assurance of retaining this narrow-channel alignment. To avoid adding additional fruit in the normal interrogator receiver (the 0.1 microsecond rise time with a bandwidth of about 10 Mc), a narrow rejection filter could be added. This type of element is common in the DME equipments which operate on both sides of the 1030 and 1090 Mc SSR frequencies. Another advantage in using the simple, two-pulse reply is that the chance of losing a reply with garbling of codes is greatly reduced since the decoding (ground) is simpler. Thus, a two-pulse reply in heavy interference (many other aircraft replying to more than one interrogator) is more readily decoded from the simpler (general aviation) code.

O. SYSTEM ANTENNAS

The use of directivity has been of considerable aid in the solution of many other aircraft navigation problems. Major improvements have been attained in ILS glide slopes and localizers as well as in the case of multi-lobe omniranges. The signal variation in the transmission path can vary by as much as about 25 db when the lobing of ground antenna patterns, serrations and lobes of the aircraft antenna pattern, and aircraft attitude (bank in particular) are considered together. This is equivalent to varying the range from about 35 to 500 miles. The ground lobing is fixed in vertical angle for a given antenna height (as shown in Figure 25); lobing is more pronounced when the antenna is near the ground. Typical heights of a few feet to 100 feet are often employed, changing the position of nulls (Figure 26). However, vertical nulls are typical of the SSR system and must be accounted for in the signal transmission estimate.

By increasing the height, three important factors occur: a) the number of nulls per unit vertical angle increases in a manner proportional to height, and b) the depth of the nulls often becomes less with height, since the large area that creates the nulls from the "Lloyd's Mirror" principle becomes greater and the irregularity is correspondingly greater as the likelihood of irregular terrain or objects being in the first Fresnel zone increases, and c) the line-of-sight increases, so that lower altitudes at greater distances are reached. Tacan tests at adjacent frequencies illustrate this point clearly.

Unfortunately, little of this potential system benefit has been introduced to date into the SSR system and could have pronounced effects on the practicality of a low-cost low-power transponder. Since much of the signal gain in the system must fill the "holes" created by nulls, the overall performance would be enhanced by elevated sites. "Height-gain" is clearly possible, resulting in better low-altitude coverage where most general aviation aircraft operate (1 to 5 thousand feet). Interrogators on towers around
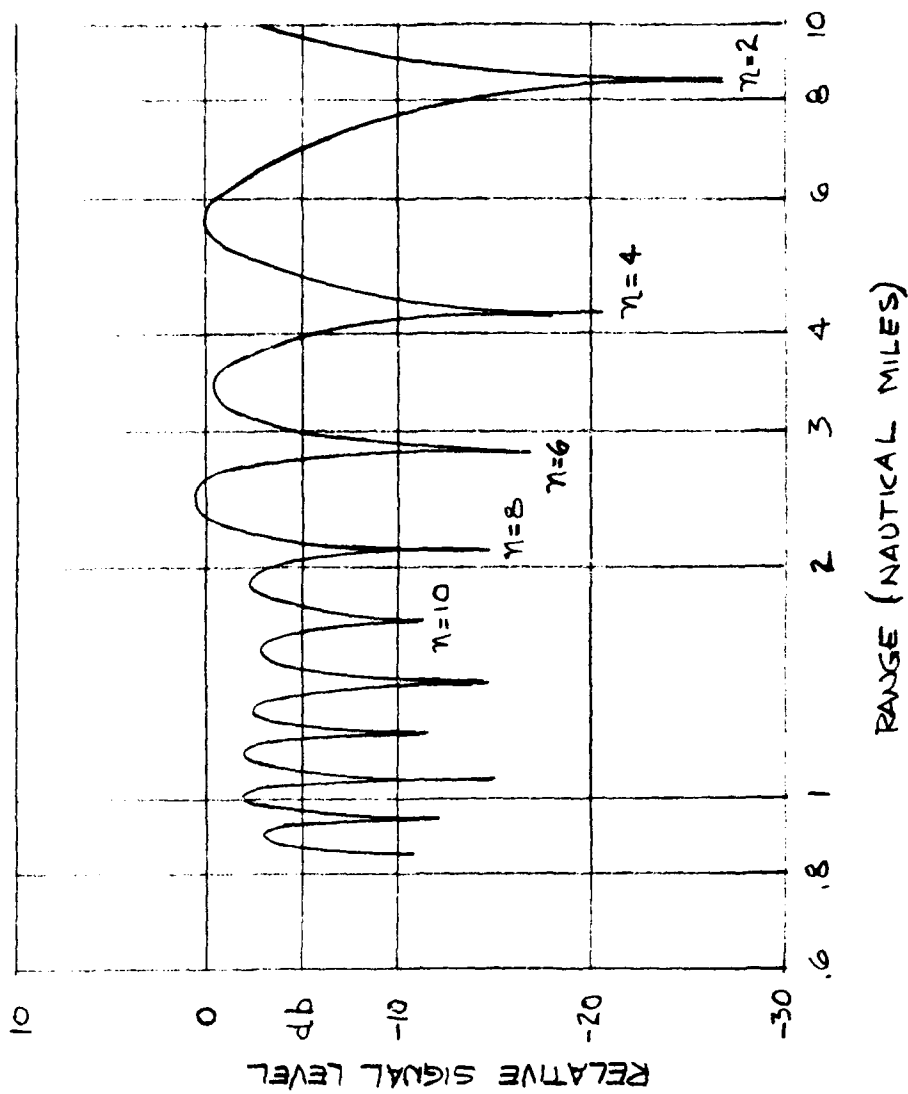
POSITION AND DEPTH OF VERTICAL NULLS
FOR ANTENNA 26 FEET ABOVE GROUND

FIGURE 25

90
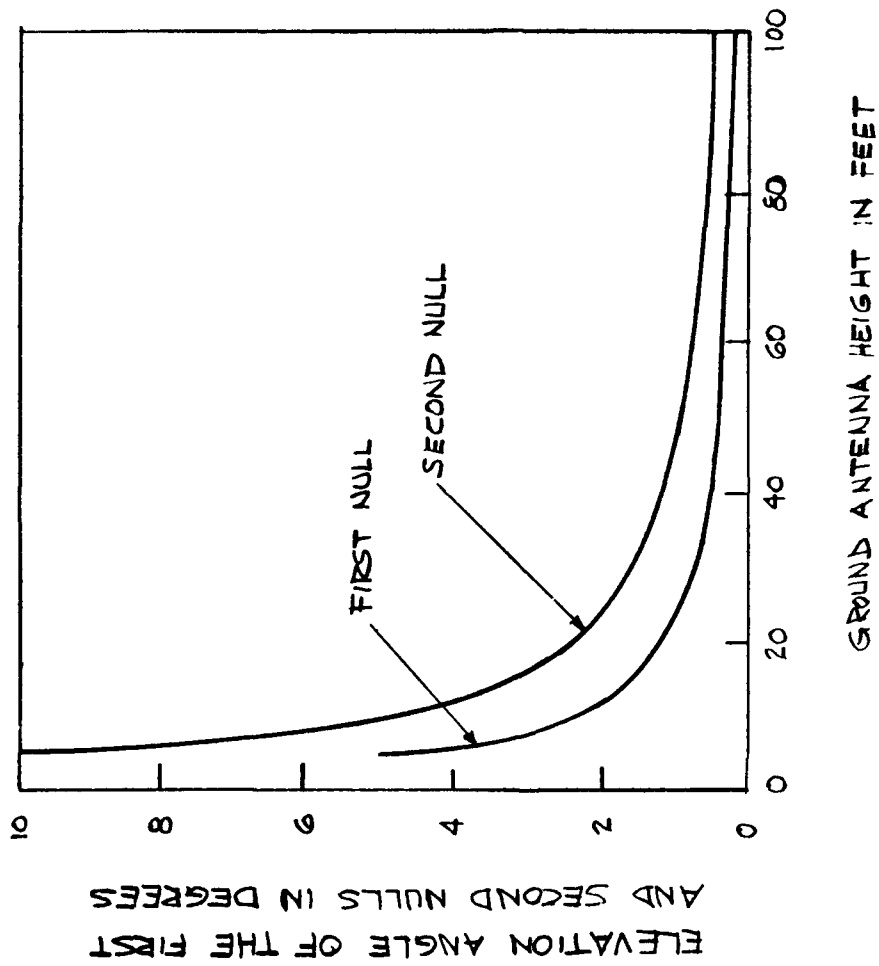
ELEVATION ANGLE TO THE FIRST AND SECOND NULLS VERSUS
ANTENNA HEIGHT AT 1150 Mc OVER A SMOOTH SPHERICAL EARTH

FIGURE 26

91

50 to 60 feet in height would be quite beneficial for this coverage. Normally, the siting criteria for an airport (primary surveillance) radar calls for the rotating antenna to be near the ground to mini- mize ground clutter and to enhance the utility of the MTI (moving target indication) at useful ranges. Most SSR interrogate antennas are mounted on the same rotating antenna structure.

Since the SSR is not limited in any way by the same problem of ground clutter, it should be sited differently; however, these radars are usually mounted on the same rotating pedestal. A narrow horizontal antenna around 20 feet wide is attached to the ASR or ARSR radars. Since the radars have large reflectors, this unit adds little additional load and is thus co-located and locked in rotation with the primary radar. This is important in ATC; however, some variations can occur if synchronously rotating, but separated units are used for the primary radar and the secondary SSR radar functions. It would seem to be a small price to aid the system characteristics by encouraging the utilization of low-cost low-power transponders by general aviation aircraft. Small airfields would not have this problem since only "free" rotating SSR antennas would be involved and best rotational speeds selected.

Tall buildings standing alone are good potential sites, and many areas offer this possibility. Since almost all SSR data is processed to narrow bandwidth and remoted over phone lines, this remote type site could readily fit the system.

At first the thought of connecting two aircraft antennas together at the receiver input sounds unrealistic since the inter- ference pattern of two spaced antennas is characterized by many deep nulls. However, several installations on certain type aircraft have been used where the first antenna blade is mounted forward and on the top side of the aircraft and the second blade is mounted underneath the aircraft near the tail. This avoids wing shielding in a turn, and the lobe structure with some aircraft is fine enough that the normal heading and roll instabilities of a couple of

degrees tend to prevent a constant bearing (null location) to the ground interrogator. This has the disadvantage of one long cable run (to the tail), but the advantage of employing existing, production, L-band blade-antennas. Such an arrangement would also be advantageous when nose and tail sectors are pointed toward the interrogator, since the number of lobes increases with the angle off the aircraft axis; thus, wide lobes would result in good forward and aft coverage. Furthermore, wing shielding due to banking (the current most difficult problem) would be greatly reduced. Comparing this with the cost of a newly developed blade antenna with stacked elements to achieve more gain should be instructive as both approaches have complementary advantages. Actual testing on light aircraft would also be beneficial since most available data is on DC-3 and larger type aircraft.

The Tacan band is nearly the same as the SSR band, so that some selected Tacan flight test data is useful in SSR evaluations. An NBS report (reference 15) on Tacan testing gives typical results. This flight test data involved a flight with ground antennas at different heights above the surface. The 18-foot-high Tacan (ground) antenna had vertical nulls with maximum to minimum ratios of 25 db for the first two deep nulls. The nulls of the 30-foot installation had less depth, and the nulls of the 315-foot installation were hardly noticeable. The available data indicate that there is a multiplicity of lobes for given vertical angles with these heights, and the so-called "height-gain" and range extensions are evident by examining these published comparison tests.

The stacking of two small discone antennas, one above the other, in a single unit would appear from the exterior to be slightly larger than the typical VHF communications "blade" type antenna. The presently used single-element unit is so near the aircraft skin that it radiates mostly a hemispherical signal with lobing and with little gain near the horizon. The stacked unit

might increase the angular coverage, because the electrical center is above the aircraft skin; furthermore, the added vertical directivity (not too much f(rmal bank angles) will enhance the signal by about 3 to 6 db in   .ect gain and perhaps another few db by minimizing the nulls near the horizon because the aircraft skin acts as an antenna.

As noted previously, the addition of two of these aircraft antennas one on top and the other below the fuselage would take care of the serious shielding encountered when the aircraft banks. This is prevalent in the current installations and is a serious problem since, when maneuvering takes place, target "hits" can be reduced for a rotation or two of the radar. ™h? pilot could use a simple toggle switch to select one or the   . furthermore, a simple timing circuit could switch between un(.wo antennas in a turn, so that one would be radiating in an unshieldt.i attitude toward the ground. Detailed antenna measurements on actual general aviation aircraft would be needed to determine the best action for this element of gain. At small airports, the SSR radar could rotate at more RPM's than in other cases, since the maximum useful range is reduced considerably. This would aid in achieving more samples per unit time, so that banking, shielding, and aircraft lobes would be less detrimental to sustaining a "track" on the display.

P.   GROUND PROCESSING EQUIPMENT FOR SSR

The SSR reply signal is often so strong that a response occurs on the side lobes of the interrogator antenna even though they may be down as much as 25 db relative to the main beam. The variation of gain with range, known as STC (sensitivity time control), causes the receiver gain to vary with the transit time of the pulse in space so that full gain is used at the maximum range (beyond, say, 40 miles) and a much lower gain is introduced at shorter ranges. The "taper" of the STC curve and its dynamic range is variable also. With the wide variation in lobing and aircraft antennas (amounting

to as much as a 25-db variation), STC is not always helpful. It
is usually replaced with SLS (side-lobe suppression).

In those cases where SLS is used, an omnidirectional pulse
is transmitted that is received in the same airborne receiver to
inhibit the reply of the airborne transponders. By comparing the
omnidirectional and beam signal amplitudes, the transponder replies
only when the main beam is larger than the omnidirectional signal.
This occurs, of course, when the beam is pointing at the aircraft.
This technique requires the reception of this SLS pulse and some
processing circuitry in the aircraft. Furthermore, many beacons
use a low-power switch to further reduce "over-interrogation" by
the ground units.

The low-power low-cost transponder would be adversely
affected in an ATC environment with a population distribution of
signals mostly in the 500-watt region with STC. Low power may not
be affected nearly as much with the newer SLS technique which is
being implemented throughout the country. Furthermore, the low-
power transponder does not tend to add as much additional interference
in the system as do the high power units.

The current digital data processing systems take the total
number of pulses from the beam (above SLS level) and "weight" them
to find the center of the signal. This equipment appears to be
compatible with the simpler codes (bracket only and identification)
and with the lower power. Thus, the national implementation programs
for improved SSR would not appear to inhibit the use of low-power
transponders but are generally conducive to their use. The potential
addition of a parametric amplifier in the ground receiver would,
of course, increase the signal level of all signals being received,
assuming that there is no clear channel for the low-power transponder
signals previously described. This would bring up the levels of
the lower-powered transponders. Whether this would add to the
interference by introducing pulses previously below the sensitivity
level is not known. Only computer studies of pulsed densities will

indicate this for given environments (number of aircraft and number of interrogators in the air). The SLS should do much to permit the use of greater ground receiver sensitivity that is obtainable with a parametric amplifier as well as the digital processing. Tests should be conducted, however, to establish whether the general aviation, low-power signals use the same single reply path.

Q. <u>INDEPENDENT REPLY PATH AND TAPERED PULSE FOR GENERAL AVIATION ONLY</u>

The addition of a second interrogator receiver at ground sites would be simple, because the same local oscillator could be used, and a simple second receiver would be only a second narrow-band IF amplifier within the pass band of the other receiver. This narrow IF (about 1 Mc wide vs 10 Mc) is tuned to the edge of the SSR band, where the narrow channel for the general aviation aircraft (utilizing tapered pulses to minimize bandwidth) is multiplexed on the system (Figure 27).

The ease of testing this suggestion warrants some further investigation. If it is feasible with the existing units, the additional complexity to the ground environment might be only a small solid-state receiver channel and a means of introducing the output into the beacon-video channel for processing. The tapered broad (DME type) pulses could be re-shaped (sharpened) after reception for insertion into the processor. This would permit nearly an independent channel for the general aviation aircraft avoiding signal level competition on the complex and often heavily loaded normal air-to-ground reply path.

The use of a narrow band within a wider bandwidth has been successfully used before with VOR (a sub-carrier and voice signal is multiplexed within the same band pass and then separately removed). The code spacing of the low-power replies might be changed if an interference problem between the sharp (0.1 microsecond) and longer, shaped or tapered (2.5 microsecond) pulses develops. If two pulse pair spacings (differing from Tacan, DME, and SSR spacings) were used, the interference from (or to) the other two services
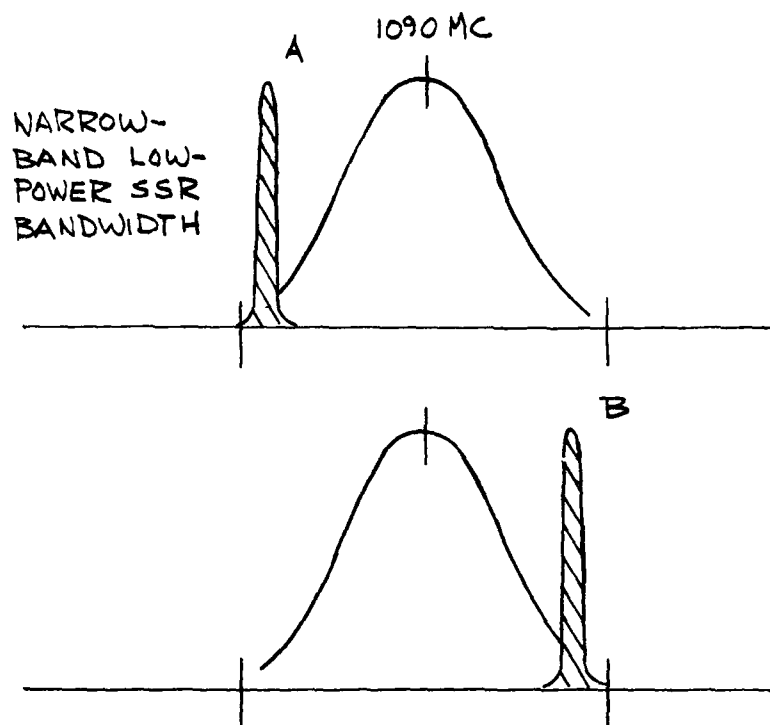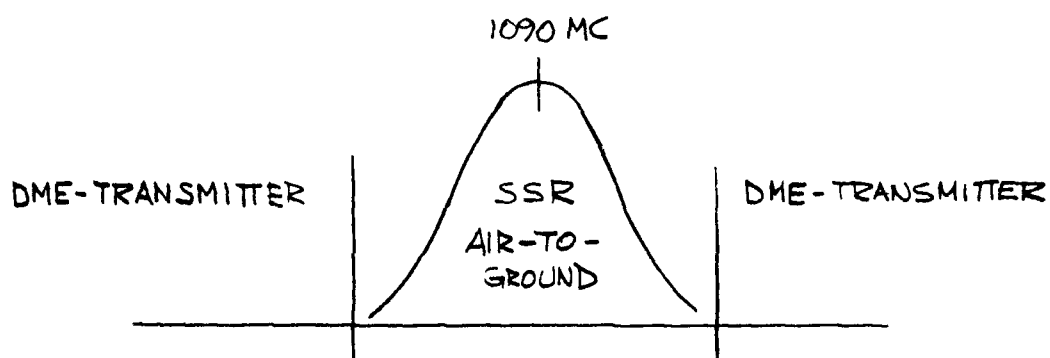
A - UPPER EDGE OF ASSIGNMENT

B - LOWER EDGE OF ASSIGNMENT

POSSIBLE LOCATIONS OF NARROW-BAND SSR MULTIPLEXED CHANNEL ACCOMMODATING LOWER POWER SHAPED (2.5 MICROSECOND) PULSE ON REPLY CHANNEL

FIGURE 27

could be eliminated by code-spacing and filtering.

For example, with a reply that uses only two broad tapered pulses for a normal bracketing pulse and two pulses with different spacing for identification, the spacing would be separated by a few microseconds from other service spacings and could be identified and decoded on the ground with the narrow band-IF of the interrogator receiver. After simple decoding, another unit is triggered to introduce the pulses into the video processing as if they were from the normal channel. This pulse code alteration is simple and would require something like a "defruiter" or storage-delay line, both available in quantity production in the SSR program.

R. CONCLUSIONS

The total system outlook is far from discouraging, and with modest investments in electronic R and D it can be evaluated. This might lead to a transponder that is in the 500 dollar region, uses wider pulses, a few watts of peak power, and two simple codes. This could greatly encourage a potential manufacturer if a program is implemented, since a market of around 25 to 50 million dollars may exist for such units. They would be as commonplace and as low-cost as VHF communication equipment. SSR transponders provide for each dollar of general aviation investment as much service as VOR, since it is possible to enter the light aircraft into "the-system" with improved service to the owner and reduced risk to himself and others under both IFR and high-density VFR.

If a means is not found to achieve this or an equivalent result, it is not probable that an independent system (non-cooperative) can be made to work without far greater costs and delays. The owner of the low-cost general aviation aircraft may not choose to buy a 2,000 dollar transponder; yet, to protect those with transponders, the primary radar program of the country must be forcibly improved. Higher powers, multiple sites, more radars, costly MTI, circular polarization, and other processing of "skin

track" signals will be needed. Federal money spent in the SSR program will get far greater results during the coming decade, for less investment. The ability of the general aviation aircraft to be accepted as nearly an equal partner in the ATC system would readily warrant a substantial development program.

The 5-watt transponder produces a ground signal that is far more useful than the few microwatts coming from a reflection off a small light aircraft. This step would be the cheapest and most timely to take on a national basis, since it is probably as effective a collision avoidance system as can be expected for a decade because of the current status of competitive,cooperative CAS technology. Even without an altitude indication (since others have it and the identification function elicits it from the pilot), a large positive step forward in air traffic control for general aviation can be quickly made.

An additional direct benefit to all general aviation comes from the fact that a low-power, low-cost ground interrogator could be installed at many small airports that could never afford an ARSR or ASR radar costing 10 to 20 times more. The use of (SSR-only) radar at a field would permit a modest tower display of the local air traffic, permitting improved IFR flight. This could be a "packaged radar" as is used in the "low-cost" ILS projects, now under procurement to bring the great value of minimum services to the hundreds of general aviation and the small city airports.

To conclude this section, a summary follows of techniques for low-cost transponders.

1. Simplified codes and lower power (around 5 watts)
2. Increased transmission path gains by use of better ground antenna siting, more ground vertical gain, and parametric amplifiers.
3. A multiplexed narrow-band service with slight range degradation permitting additional gain and discrimination by narrow IF detection. (This would provide an independent channel for the low power transponder and simpler pulse shaping.)

4. Current SLS, and digital processing and defruiting would aid in the use of low-power transponders to ranges not exceeding 50 miles.

5. An aircraft antenna could be developed that would be low in cost yet add as much as 3 db and minimize attitude fadeouts.

6. Low-cost, higher-RPM local interrogators would provide effective radar data on general aviation aircraft.

7. Only a "total-systems" look can be taken, since the development of a low-power solid-state transmitter would be useless if it could not compete in the environments of much higher power units (20 db difference).

IV. ELECTRONIC SIMULATION OF VERY LOW-VISIBILITY LANDING GUIDANCE AND INSTRUMENT DISPLAYS

A previous NASA study by the author* identifies some of the operational aspects of low visibility landing. Currently, very low visibility is considered by international and U.S agencies, such as the ICAO (International Civil Aviation Organization) and the FAA, as visual ranges of 1800, 1200, 700 and 150 feet. These are more fully defined by quantitative transmissivity measurements using transmissometers along a landing runway. The instruments determine the horizontal visibility along the runway at about the pilot's eye level at touchdown. The systems and associated authorizations are, respectively, known as CAT II-A, II, III-A, and III-B for the above sequence of declining visibility conditions. CAT III is "zero" visual range or the so-called "blind" or "zero-zero" landing, something beyond the scope of today's technology.

A pilot in a landing aircraft will view the runway and its associated visual cues such as paint, lights, texture, etc., from a point on a glide slope (line) of about 2.5 to 3.0 degrees elevation, placing the pilot some 2200 feet from the radio glide slope emitter. The visual (pilot's eye) path and the electrical-radio path nearly coincide for most aircraft, so that if one assumes that the slant visual range is the same as the runway visual range, the pilot will not see his destination or aiming point in CAT II. On a clear day he normally sees the objects around the aiming point move in different directions and velocities in an orderly and accustomed fashion, the aiming point of course remaining fixed. In the lower visibilities the aiming point is missing from the view of objects outside the windscreen. The most distant visual object is somewhat less than 1200 feet away. Usually slant visibility is less than runway visibility (as measured) so that perhaps the nearest visible object may be but 1000 feet from the aircraft in

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* "Analysis of Cumulative Errors Associated with Category II and III Operations with Requirements for Additional Research," NASW-1441, December, 1967.

an operationally typical CAT II condition. At the other extreme, the nearest object is limited by the windscreen cut-off angle which is about minus 15 degrees or approximated by a distance in front of the aircraft that is approximately four times its height (say 400 feet when at 100 feet—the so-called "Decision Height" of CAT II). Thus, the pilot sees a surface segment about 1000 feet minus 400 feet, or 600 feet long, which is depressed several degrees below the true horizon. From this limited visual information, the pilot must maneuver the aircraft to reduce the deviation errors due to normal flight and ILS radio propagation. These can be such as to cause the pilot to be viewing the runway threshold from quite different distances even though each case is at 100 feet of height. This is a consequence of the allowable variation of glide paths over certain ranges of angles and locations relative to the runway threshold.

Lateral threshold errors of the radio localizer include (3 sigma) such factors as ±25 feet centerline tolerances, course bends up to 15 feet, and airborne (receiver centering) errors of about 40 feet. In addition, the piloting deviation limits can be up to 25 microamperes or 1/6 full-scale course deviation—1/6 of 350 feet is about 60 feet. Thus, it is well within reason, when considering 95 to 99% probabilities of the lateral location of visual surface contact, to encounter from ±75 to ±100 feet of dispersion in some cases. A side-step maneuver is then necessary to return the aircraft to the runway centerline.

Various combinations of lateral and longitudinal dispersion at specified heights such as those of CAT II create situations, each of which require decisions of considerable consequence in a matter of split seconds. There is also the possibility that certain limits exist beyond which the pilot cannot safely retrieve the aircraft depending on its flight dynamics and the positional dispersion upon visual acquisition.

Added to this dispersion of position is the variation in heading that can be considerable with wind shears (unexpected cross

winds) of up to 15 knots and poor heading references. The magnetic
relationships between actual runway heading and the aircraft's indi-
cated magnetic heading may differ by 2 to 3 degrees in some cases.
An uncorrected 3-degree drift at 200 feet per second can amount to
a cross-track drift of about 10 feet per second, adding to the above
problems. In large aircraft the total lateral runway touchdown
limits with allowable cross-winds may be but ±20 to ±30 feet, assum-
ing the outboard wheels are a few feet within the runway's edge.

The airline industry, general aviation, and military
users of jets are now becoming aware of the risks in low visibility
and the differences between the CAT I and CAT II concepts. Increased
caution seems to prevail even though some operators are certified
(equipment-wise) for CAT II. Some operators are confident that
CAT II is realizable as now specified (early 1968), and others have
serious doubts. It is a matter that is amenable to scientific
inquiry utilizing realistic electronic-visual simulation. A single
landing accident of a jumbo jet attributable to the risks of CAT II
will cost some tens of millions of dollars and cannot be tolerated
with today's knowledge of simulation and system engineering. The
pioneering concept of reduction of visibility by actual exposure
to flight experience cannot be justified below the current limits
of CAT I or II-A. Recent court rulings place further responsibility
on those who authorize or assure this.

The problems that are readily sorted out in the several
seconds and large maneuvering limits of CAT I (2400 feet visibility)
are compounded many times in CAT II with its short times for decision
and aircraft maneuvering before ground contact. Poor visual inputs
to the pilot for the decision making process in CAT II are an additive
functional handicap many times the magnitude one might expect by
the mere halving of the visual dimensions--that is, the piloting
problems presented during CAT II conditions can be perhaps 5 times
those of CAT I. It is not merely the doubling of problems with
the halving of the visual range. For example, a 14-second side-step

maneuver can be completed from 200 feet (visual height) since about 25 seconds remain to touchdown (including) flare at 100 feet. This results in 10 seconds of tolerance. In CAT II the same 14-second maneuver must be completed more precisely; there is but a total time of 15 seconds with only a 1-second margin for all delays. This is a 10:1 change in timing tolerances.

The degree of risk, the economic losses of a single landing accident (that might have been prevented by fully exposing pilots to the practical spectrum of problems inherent in the operation) is becoming a national necessity before proceeding to the lower visibility limits. Those* who now believe that a new radio guidance system is needed for CAT III, and even perhaps CAT II, must recognize that flight and pilot factors must dictate the new, more rigid standards that cannot now be achieved with the existing ICAO ILS system which operates in the VHF region. The new landing system is probably going to be engineered to operate in the microwave region. However, what tolerances should be established for runway centerline accuracy, course bends, etc.?

These new criteria should be determined by clearly establishing the operational needs through realistic, full-scale electronic simulation of the CAT II and CAT III conditions. The ± 25-foot centerline error might be reduced to ± 5 feet, the bends to ± 5 feet, and the airborne receiver errors to perhaps ± 10 feet with a total RSS of perhaps 12 to 13 feet vs the ± 40 to ± 50 feet of current CAT II ILS. This must include adequate allowances for pilot deviations from the displayed course, flight dynamics, and an equitable distribution of all errors so that the 150-foot wide runways can be successfully utilized in every CAT III landing. Aborting a landing at CAT III limits is impractical (height of less than 35 feet); consequently, all wheels must be over paving. The increased sluggishness of flight response of large aircraft, such as the C-5A, 747, and SST must also be considered. They will be

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* RTCA, Special Committee 117 and DOD statements at RTCA 1966 Annual Assembly.

highly dependent on low visibility landing performance for their safety and economic justification.

A. NEED FOR STATISTICALLY SOUND CAT II-III SIMULATION SAMPLES

New flight techniques for maneuvering at very low heights, such as direct lift control, side-slip, skidding, and reduced positional dispersion on visual contact, must be developed. These techniques cannot be developed in real flight since the visibility we are discussing occurs but 1% of the time. On a poorly predictable schedule, this would mean that dozens of attempts would have to be made in an actual, fully instrumented aircraft to get one validated landing. This would cost many thousands of dollars per test landing with current (transport aircraft) costs. In a place like Arcata, California, this cost could be reduced since its weather and high probability of low visibility has a long history with the Weather Bureau and the National Bureau of Standards. If a test aircraft were on standby at Ames Research Center during the best few weeks when low visibility historically occurs in actual flight, data of considerable value could be collected.

Nevertheless, this points up the impossibility of obtaining a statistically significant sample (say 100 CAT II approaches under one set of conditions—aircraft type, runway type, glide angle, etc.) by actual flight testing in an actual aircraft. Even so, the actual flight tests should be done in connection with the simulation to assure realism and to check on the validity of the simulation. However, for every CAT II landing in an actual jet aircraft, perhaps 1000 can be made in the low visibility simulator. In simulated CAT II, under controlled and measured conditions, several thousand landings with variables are tested statistically. If different aircraft types and various conditions (say 5 to include the spectrum of present and future civil and military aircraft), current and new models, 2 runway widths, 3 conditions of lateral dispersion, 3 conditions of longitudinal dispersion, and 3 conditions

of vertical dispersion are all used, this would quickly result in 270 sets of specific conditions, each of which must be validated by 3 pilots making, say, 10 approaches under each condition. This will generate a total CAT II sample of about 10,000 landings that would have statistical significance--that is, far more meaningful than allowing airline operations to do so until an accident prevents further samples. Variations in visibility, landing weights, etc., could readily increase this sample size at some future time after the first few thousand samples have been statistically treated for 3 sigma and 5 sigma results (commensurate with the fatal nature of landing accidents).

B. ELECTRONIC TECHNIQUES FOR SIMULATION

Several simulators that essentially consist of a TV camera driven on a mechanical track system, and that are caused to view a precision scale model of an airport, are in existence and have proven valuable in visibility tests of perhaps ½ to 1 mile or more. Ceilings are often simulated by simply showing the unattenuated view below a given height. This is not realistic, since the view may include the scene of the runway some 8000 feet long with all the needed cues of vanishing points, aim points, etc. By using a masking technique to limit the most distant object visible in the scene (say 1000 feet), some realism is added. The decreasing brightness and contrast of the normal low-visibility "real-life" scene is not realized and could be a serious oversight in such an attempt at a realistic simulation, the results of which are used to formulate critical decisions. Even the use of such simulators to expose pilots to what they will actually see in the low visibility situations is worthwhile. The utilization of the limited visual cues to make vital decisions that are often complex in nature (often more than a go no-go decision) is strongly urged since precise maneuvering with poor pitch references is essential. Inadvertent surface contact, perhaps partially off the paved surface, is possible. Each decision is one to execute a specific precision

maneuver from a host of potential maneuvers. For example, a slight lateral error may be acceptable if the heading and the cross-track flight path are obviously correcting in the right direction. But, how long to wait to see whether this is true or just an illusion of a wind shear that is rotating the aircraft in heading giving the cross-track illusion? Remember the pilot is up to 100 feet ahead of the lateral turn axis, and illusions often quickly detected and ignored in good visibility may be accepted as true situations in low visibility and a decision is made that includes illusionary and false visual guidance information.

Thus, electronic simulation must be able to create the "scene" in sufficient detail to be convincing to the pilot. Modern digital computer techniques can store the dimensions of all objects in a "computer-graphics" format. In some applications the computer provides an analog read-out through a conversion means, driving automatic drawing tables or plotters. Movies are often made this way simply by making one frame at a time as in a film animation. Films made of the pilot's view as he approaches an aircraft carrier are highly realistic as are some prepared by the Boeing Company of the scene from the cockpit of a jet liner landing at a civil field.

Other techniques of computer-generated visual scenes use a cathode-ray tube display that shows the pictorial representation of the computer's output. The computer can be programmed to view the stored scene from any angle, any perspective, and at any range. Thus, a dynamic real-time scene can be created in a purely synthetic manner that can be projected for pilot usage with a wide screen display. This has been done successfully in a few cases, and the computer inputs can be varied in a closed-loop manner by a pilot maneuvering the controls of a simulator cockpit. He can cause the computer to create in real time the scene that he would observe as he is maneuvering (displacement and attitude) toward the landing. The next step is to determine how to control the scene that the pilot observes so that objects at a specific visual range are seen,

and those beyond are not visible. Variation in brightness and contrast to minimum range (just as in the "real" world) is probably most important to obtain pilot involvement in a realistic sense.

The computer program must then have added to it the computation of range to each object, so that a form of moving plane or spherical surface precedes the aircraft position a specified amount, in accordance with the assumed or simulated visibility range. This could be electronically controlled by the operator of the simulator, so that specified amounts of visibility are provided for a test of a subject. By this means, a comparison of the presence or lack of certain visual cues can be made. Familiarity with what a dynamic, low-visibility scene really is like and what various cues are used to visually determine the best maneuver should aid considerably in establishing visual aids. With a new set of ground rules for applying visual inputs to the normal piloting decisions, safety can be improved.

There are in such low visibility conditions several possible illusions such as cross-track drift and slowly changing heading, mistaking lights of one form for another (centerline vs perimeter lights, the observation of a depressed surface that is well below the runway elevation (bottom of a gully in the approach area). This illusion assures the pilot that what he sees confirms that he is adequately high (or perhaps too high), causing a misjudgment of sink-rate or height. He is consequently not only unprepared when arriving over the rising terrain near the runway threshold, but then receives another misleading illusion: that of an excessive sink-rate due to the apparent illusionary rapidly rising terrain. Many such visual illusions exist that can be so convincing to the pilot that, if he is not aware of them, some can be fatal. Another simple illusion is the variation in runway widths. This variation is from 150 feet to 300 feet, or two to one. A few lights outlining an edge of the runway and centerline lights (seen vaguely through an overcast) may give a height illusion over threshold and the runway itself that is in error by 50%. The subtended angles at a height

of 100 feet for a runway that is 300 feet wide is the same as
the subtended angle of a 150-foot-wide runway at a height of only
50 feet. At 100 feet, sink rates of 10 to 12 feet per second might
be acceptable, but at 50 feet they are not acceptable, since the
reduction in sink rate before contact requires several seconds with
some aircraft*

The electronic means for doing this must be flexible enough
to include "scenes" of all types: variation in runway widths,
varying aiming points, terrain profiles preceding the runway, and
of course, the ability to present any given slant visibility.
Since visibility is the most critical matter in CAT II and III, more
emphasis and realism are needed. For example, there are various
types of fogs that prevail in different parts of the world where
the variation of density with height differs. Some are very treach-
erous where the pilot, looking through the layered overcast at a
steeply depressed angle, sees the surface clearly; then, upon flare
and touchdown, while attempting to look horizontally through a long
transmission path for lights or visual cues, he is suddenly without
adequate cues. This should be electronically programmable in the
computer and display. Even for a given visibility, sometimes the
runway visual range instruments indicate a rapidly changing visi-
bility in but a few seconds. Snow, rain, and excessive lights
partially blinding the pilot due to particle scattering are other
desirable features that should be simulated.

C. COMPUTED FACTORS

In the computer-graphics concept, the "scene" is stored
electronically in the computer. The amount of storage depends on
the details of the scene. The extent of the scene could be extremely
limited since the first visual surface cues are probably not available

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* Other visual landing illusions are discussed by Donald G. Pitts,
  USAF School of Aerospace Medicine in "VISUAL ILLUSIONS AND AIR-
  CRAFT ACCIDENTS, SAM-TR-67-28, April 1967.

until the pilot has descended to a height of about 150 feet for CAT II, and even then the visual surface segment is but about 400 feet in dimension. This is roughly the surface between two spheres 1000 feet and 600 feet in radius (centered on the pilot's eye), the actual scene of the depressed surface segment is that encountered in about 2 seconds of flight. This infers that the actual computation of the displayed surface objects is reduced considerably with respect to a scene that might be a few thousand feet in dimension, involving far more objects and computations. Thus, the computational load of generating the images (lights, runway markings, edges, surface texture) in "real-time" is reduced since so little is visible that must be shown to the pilot.

The number of objects requiring computation increases as the pilot nears the ground and starts the flare maneuver in which the flight path angle in space (not aircraft pitch or body angle) changes from a nominal 2½ degrees to a final ½ degree at touchdown. This 5 to 1 change in flight path angle takes about 3000 to 4000 feet of forward flight from a critical height such as 100 feet and encounters large changes in the pilot's visual surface segment. At touchdown nearly the full 1200 feet of scene must be shown in CAT II simulation. The vanishing points of the runway, its centerline, lights, and markings now appear. The surface here is a plane cutting through two spheres about 1200 feet and 80 feet in radius. The display of the surface (1120 feet) between the spheres is consequently generated at shallow (½-degree) viewing angles.

An electronic problem in the display and computation of this scene is readily identified in these two examples. In one case the most distant objects are viewed at angles only about ¼ to ½ degree (depressed) from the horizon (touchdown). In the other case, objects up to 8 to 14 degrees below the horizon must be computed in true perspective and displayed. In one case the visual path is through atmosphere that, if laminar in form, can be different from a visual path through the same partial laminar obscuration at

8 degrees. The objects will be more distinct in the 8-degree case
as they move at high velocity toward the pilot (assuming him as
the reference point in the computer program). The objects moving
toward him increase in depressed angle (and clarity) to the maximum
of cutoff, say 14 degrees. The computer program, therefore, cannot
have a constant change of object brilliance or contrast with
changing range.

In establishing range to the most distant object, the
computer will thus bring the object into view with the minimum per-
ceptible contrast and brilliance commensurate with the background
(such as fog or other weather obscuration). However, as the object
moves toward the pilot, it will follow a path characterized by
angular and linear velocities that will vary with its location rela-
tive to the flight vector aiming point of the aircraft at the moment
of computation. The contrast and brilliance must then be recomputed
for each of these object movements at, say, a 30-cycle rate and not
simply assumed to be a constant for a given range.

Furthermore, in the computation the height of the aircraft,
its cutoff angle and (of course) full, 3-axis motion must be included
as in any realistic flight simulator. (Most of the obvious needs
fulfilled by past simulators are not discussed here. The electronic
needs to create a realistic low-visibility scene add a major new
capability.) If a visibility is assumed through a homogeneous over-
cast or obscured atmosphere, then calculations are easier. If a
laminar layer exists as it does in certain parts of the world (only
a few dozen feet above the surface, with increased density toward
the surface), this must also be considered. It prevails in many
parts of Western Europe according to some authorities. This is
another serious illusion that can cause a pilot to feel confident
upon acquiring his initial visual contact height and suddenly realize
in the flare (where he must now view directly through the layer
rather than cutting through it at a large angle) that his visual
references are suddenly destroyed. Continued exposure to fully

realistic situations like this will be the only way eventually to develop adequate experience in CAT II or any of the CAT III conditions, since they are generally so rare that continuous updating of experience will not be possible. In fact, under the current FAA AC 120-20 procedures a pilot can be fully qualified who has never witnessed such a visual phenomenon nor has he ever been exposed to an actual 1200-foot runway visual range (RVR) and perhaps an associated 900 to 1000 feet of SVR--slant vs runway-visual range.

With today's criteria, the only visibility reported to the pilot is his RVR. This is in reality the transmissivity of the atmosphere along a path 15 feet above the ground, parallel to the runway centerline, but about 500 to 1000 feet from centerline. A base line of 250 or 500 feet is used between the transmissometer photocell (receiver) and light projector (transmitter). In the electronic computer-generated low-visibility scene this variable-- measurements at one place and pilot vision through the atmosphere at another place and along a geometrically quite different path-- must also be considered. Pilot advisory information in low visibility is based solely on RVR. In some cases the visibility from the cockpit can be better than suggested by the RVR measurement, and in others it can be worse. The pilot must first learn to adjust to the relationship of the slant visual path from a 150 or 100 foot height relative to the RVR path. By continued exposure to a realistic low visibility he should learn to expect the best and the worst and be provided with some experience in exercising judgment and expediting the split-second decisions he must learn to make with limited data.

D. COMPUTER SIMULATED DISPLAYS

The electronic simulation of displays that might be used in the so-called "heads-up" concepts is also important. Since these are usually projected displays, the computer should be able to simulate them electronically. It is already evident that the several

competitive "heads-up" displays use different symbology and different
optical-visual projection means. The "microvision" concept of display
actually receives radio signals from 8 microwave beacons outlining
the runway as if they were 4 equally spaced lights on each side of
the runway. Target scintillation, ground reflections, and multipath
cause these beacon images (after being processed by a monopulse
receiver equipment aboard the aircraft) to "dance" slightly around
their actual position. The slight movement of one or two of these
may give illusions of increased height or lateral misalignment. The
electronic simulation of these types of displays (microvision, beacon
vision, etc.) in a fully realistic but synthetic manner can resolve
many problems of assessing their value to the pilot, establish human
factors criteria (for example, how many points outline a runway
adequately), etc. This should be done before the tens of millions
of dollars are spent in equipment development and installation.
Too little is known of their real value to the pilot in low visibility.
"Real-life" testing in actual CAT III conditions is too costly and
hazardous.

An example of another type display is one in which images
are computed from the actual ILS data, such as the glide slope,
localizer, DME, and radio altimeter. The aiming point of the air-
craft and runway perspective and alignment are thus displayed, but
only to accuracies of these radio guidance inputs. In so doing
some assumptions must be made about ILS errors, terrain effects on
radio altimeters, etc., since the pilot's display is simply symbology
driven by servos (or electrically) from the (ILS, DME, radio alti-
meter) derived position of the aircraft. If the ILS errors are,
say, 40 to 50 feet at threshold for the localizer, the pilot will
have a "heads-up" display of the aiming point and runway symbology
that is misaligned by this amount. In the visual sense a misalign-
ment of this magnitude probably cannot be tolerated.
Figure 28 typifies this. The pilot factors study using the
computer-generated landing scene and computer-generated "heads-up"
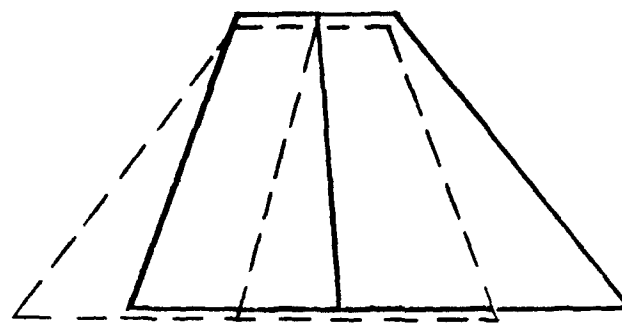
LATERAL MISALIGNMENT
(ABOUT 35 FEET)
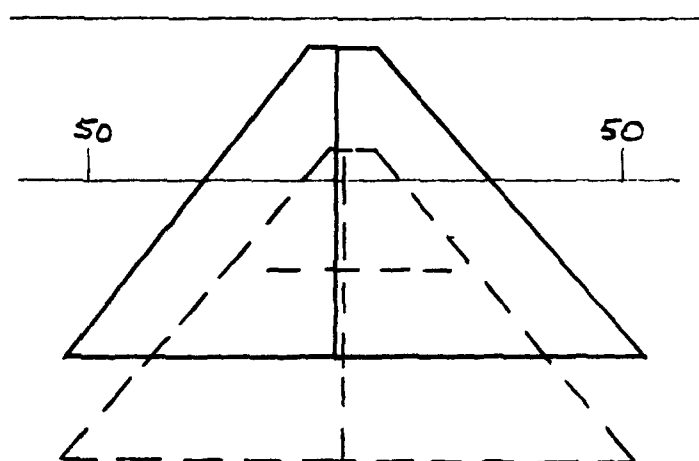
50   50   AIM POINT
                  1000 FEET
                  2.5 DEG

LONGITUDINAL MISALIGNMENT
(ABOUT 500 FEET)

— — — DISPLAY
———— ACTUAL VISUAL RUNWAY

TYPICAL HEADS-UP DISPLAY BORESIGHTING ERRORS

FIGURE 28

display should be able to establish how much misalignment is tolerable between what the pilot sees of actual ground images and a "heads-up" display before confidence is lost in the concept. Boresighting in all 3 axes of flight as well as aircraft position is essential to generating pilot confidence.

One can only estimate at present what the alignment accuracy of the symbolized world of the "heads-up" display should be with respect to the real world that does appear through the same windscreen. The serious loss of pitch reference in viewing depressed surface sectors could be replaced synthetically. It is likely that all lateral errors on a 3-sigma basis must not exceed a value of about 10 feet to gain pilot confidence. Heading errors between actual aircraft axis and the runway centerline vs the displayed heading and displayed centerline are equally significant. A computer can easily sample these errors. The pilot will often be prepared, because of the anticipation provided by the "heads-up" display, to initiate a certain maneuver upon visual acquisition of any ground objects. If the ground objects appear displaced an excessive amount, say 40 to 50 feet laterally, and the maneuvering limits of the aircraft—2 degrees of bank and about 20 to 30 seconds for any reasonable side-step—do not permit this correction, he has been "suckered" into a highly vulnerable situation by the display. Such displays have a risk of causing added confusion since the pilot's mind, already prepared for a given circumstance, must now be changed, taking longer than a case of not having been preconditioned.

The electronic synthesis of several such displays with computer-graphics techniques is another valuable research tool. When combined with the computer-generated low-visibility outside-world display, the allowable perturbations, typified by radio guidance, can be added and evaluated with differing symbology. Some symbology may be less demanding of input accuracy. Wind-shear, variable visibility, etc., all seem to be readily synthesized singly or in various combinations. Much needed, significant research can be conducted on the interrelationships between the pilot, his visual

guidance cues, his display of radio guidance, and the flight dynamics of the specific vehicle he may be flying.

Large, heavy, long-bodied aircraft have responses to controls that are sluggish and require a greater attitude change to achieve a given change in flight-path angle.* This increased attitude change, in turn, is needed to correct displacement errors vertically, laterally, and longitudinally. An entirely new set of conditions may prevail for such aircraft over some of the existing, more familiar, low-visibility experience. Extrapolation is no longer possible from 707 data to 747 or SST aircraft, because the fundamentals between the aircraft have been changed markedly. Vulnerability to cross-wind (allowable up to 15 knots in New York for noise abatement) should be examined. Greater heading corrections may be needed in a cross-wind to reduce lateral displacement errors from runway centerline.

As one simple example of this matter, the 747 has an outside main landing gear width of about 42 feet. The localizer antenna that provides the centerline reference for the landing and roll-out will be about 110 feet ahead of the line through the main gear (rear ones). In a cross-wind that creates a 7-degree crab and a 3-degree heading maneuver toward the centerline (totaling 15 degrees), the aircraft's antenna cannot be more than about 25 to 30 feet from centerline to assure the pilot that the unseen outside wheel is no closer than 5 to 10 feet from the edge of a typical 150-foot wide runway (reference 16). This is to say that the culmination of radio and visual guidance from the CAT II limits to threshold must not exceed 20 to 30 feet under these 747 landing conditions. Currently, the radio guidance permits up to 40 to 50 feet and FAA document AC 120-20 allows the pilot flight following errors of 25 microamperes or 25/150 x 360 feet or 60 additional feet. If added together, as may occur occasionally, these two

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* George Cooper, "SOME RECENT RESEARCH RELATED TO APPROACH PROBLEMS," NASA-Ames, presented at the Flight Safety Foundation, December 1967.

errors exceed what is reasonable in cross-wind limits of maneuvering
by 4 to 5 times if, say, 5 cases per thousand are considered. Most
analyses of this type consider one case per million or about 6 sigma.
The above is about 3 sigma.

The electronic simulation of the visual cues for landing
the 747 in CAT I and CAT II conditions is urgent at this time before
arbitrary limits are placed on its low-visibility landing performance.
The effective reduction in useful runway width by doubling the gear
outside dimensions (compared with those of a typical 707 or DC-8),
when added to crab-angle errors of body length and then added to
poor response, are three factors that severely reduce the useful
amount of cross-wind runway width. This, of course, is related to
the aircraft control point--the localizer antenna itself. Maximum
permissible cross-wind deviation from centerline for a 747 is less
than half that of a 707. Of course, as previously noted neither
aircraft can be assured of this positional accuracy with the existing
ILS system criteria. In electronic simulation of this matter, the
ability to vary the 3-axis response representing two such aircraft
and their physical dimensions that create these matters must be
fully engineered into the simulator design for realistic testing.
With the advent of aircraft that may have a localizer antenna (or
pilot's eyes) as much as 200 feet ahead of the main gear (when
mounted in the nose, the most likely location since propagation may
defeat its location anywhere else), a change in heading of 6 degrees
can cause the aircraft antenna to move 20 feet, displaying to the
pilot a 20-foot error that does not exist at the main gear location.
Ten degrees would be 35 feet. Consider that this can be ±30 feet
in allowable winds. To do a side-step, one must first turn the
aircraft adequately in the direction to reduce the displacement
error. This calls for a roll to a given bank limit and then holding
the banked turn to the new heading. Roll-out and level flight in
the direction of zero error must occur first and then the reverse
sequence: roll, banked-turn, and roll-out to wing level. This must

all occur before the flare height of from 35 to 60 feet depending on flight path angle response to pitch change. Since a large enough "bite" angle to provide a heading change is possible from either side, some ±30 or a spread of 60 feet of pilot eye motion must be considered. This phenomenon of the 60-foot illusionary change that doesn't occur in the main gear or aircraft center of gravity can be significant with such large aircraft.

Here, the simulation of flight to much higher accuracies is needed to assure that all gear will be over paving by a safe amount on main gear touchdown. Bank limits of only 2 degrees below 100 feet have been suggested by ICAO. Often the pilot will have no realization that one main gear may not be over the paving in CAT II and III conditions in the large new aircraft, and he again must be exposed to this repeatedly in realistic simulation to learn these minimal, but critical, visual cues. Training in the actual aircraft merely to obtain a feel for the readily identified illusions, errors, handling problems, etc., is too costly. Furthermore, such a realistic, low visibility, electronic simulation facility should permit far more objective criteria for pilots, aircraft, and radio to be established than low-visibility conditions that now exist.

E. SUMMARY OF COMPUTER-GENERATED LOW-VISIBILITY LANDING SYSTEM REQUIREMENTS FOR CAT II AND CAT III

1. Since such fine details are involved in the visual scene and yet often their extent is limited in visibilities of 2000 to less than 700 feet, image realism is far more significant than in past simulators used for landing studies.

2. Objects in the visual surface segment must appear from a nonvisual condition to visual threshold naturally and increase in contrast and brightness naturally.

3. Full flight dynamics of the aircraft (all axes, true responses in pitch, heading, bank limits, etc.) must be simulated and be adjustable to represent the most responsive to most sluggish aircraft.

4. Illusionary conditions due to long-bodied aircraft, depressed visual segments, loss of pitch reference during visual surface observation, etc., must be included.

5. An ability to set in quantitatively the RVR or SVR by a direct control of the computer-generated scene is essential. Limits from about 150 feet to 4000 feet in small incremental steps between 150 and 2400 feet are required.

6. The ability to test displays such as "heads-up" displays projected in the windscreen area, and thus also be in the pilot's vision when viewing the dynamic, low visibility landing scene is advisable to justify the simulation costs.

7. The ability to synthesize displacements out to 3 sigma of the ILS tolerances and flight-following tolerances established from manual, automatic and semiautomatic landing criteria of AC 120-20 must be included to test the potential hazards of the "three per thousand" or the "one per million" case.

8. Flexibility of aircraft windscreen, pitch, etc., must be included to accommodate aircraft typified by the 707, 747, SST, C-5A, B-58, F-111, VSTOL, etc., to assure objective results that will be needed for qualification of these and other specific aircraft in low visibility.

9. All information must be in real time, with no lag in display generation of the low-visibility "outside-world" or the synthesis of a pilot display. Even delays of a millisecond must be considered since such visual, small-rate cues are apparently used by the pilot. (For example, a slight movement of the aiming point a few hundredths of a degree over a second or two may be significant.)

10. Full performance recordings (charts, computer program, etc.) of all axes of flight, all trajectories, parameters and time should be included as well as a pictorial (video-tape) record of the actual low-visibility landing test scene.

11. The storage of perhaps 40 of the most critical CAT II runways in full dimensional detail is essential for realistically simulating the variables of runway length, glide path location and angle, runway width, specific lighting systems associated with each runway (each is different),threshold conditions and terrain profile and features for the first view at about 150 feet, runway markings, etc.

12. A computer-generated storage of actual high-resolution photography taken of the runway at various locations determined by the geometrics of the landing maneuver (and its outer tolerances) should be considered in the design for exact realism. Potentially, a computer scan of high-resolution film, by means of video type cameras of high resolution, could provide this computer-memorized

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scene directly into storage. It could then be varied by computation of viewing angle and change of range relative to the original photography. Say, 10 steps so stored with computer interpolation may improve realism of scenes.

13. If TV line structures are used in the synthesis of the scene, the number of lines must be adequate not to diminish the realism of simulation.

14. Full hemispherical views (side vision, etc.) must be available with appropriate cutoffs that vary with aircraft type and flight attitude and flight path.

15. The simulator design must include parameters suited to psychological testing of pilots' visual ability in highly obscured situations such as CAT II and CAT III. These include time of search for visual objects (lights,etc.), visual acuity, light level adaptation, color detection and recognition in overcast, identification of objects (vs merely their detection), display clutter, and resolution. The characteristics of the eye to detect slight differences in brightness, its angular resolution, and ability to estimate the speed of apparently moving objects in the field of vision must be accounted for to assure objective results. Experts in the field of (a) human vision and (b) vision through the atmosphere (different specialties) should be consulted to assure the maximum of realism from the psychological and meteorological standpoints.

F. PRELIMINARY TESTING OF DESIGN CRITERIA FOR A LOW VISIBILITY SIMULATOR

It is likely that, though the computer technology would perhaps permit such sophisticated scenes to be generated and controlled in real time and in accordance with a pilot-maneuvered aircraft (simulated), the cost of achieving some of the results may be prohibitive. As a first step in the direction of cost vs results, the technique of converting from a computer-generated scene to an automatic drafting or plotting table to an artist touch-up, frame by frame as in animated movies, should be pursued. First, the number of frames is minimal, since the actual time from a CAT II visual condition to touchdown is less than 20 seconds, and the number of objects visible at any instant is few. These films can be made by a computer that is programmed for several landing trajectories. Included in the program are the tolerances and profiles of actually measured flight paths. These films can then be used to

study the necessity of certain details such as color, day or night scenes (night is probably easier), and the realism of the method of SVR and RVR simulation. The fading of objects with range and the initial appearance of objects at specified ranges between 1200 and 150 feet of visibility can be tested with film. Such a series of films may seem at first a complicated way to approach this problem; however, they can be generated for a very small fraction of the cost required when using the large, real-time computer that will finally be needed. Since the film can be made over a period of days and does not require real-time computation, this allows more flexibility in most aspects of the intitial testing of the ideas, the amount of cues, etc. Results can be used for establishing more realistic specifications and simulation criteria than can now be written with confidence. Each of the 15 items listed can be examined for its contribution, and some compromises may be evident.

For example, the subject of line structure of a TV type scanned scene when employed in the real-time, dynamic, simulation of low-visibility landing can be examined quickly and cheaply by film. The slow but low-cost method of preparing a film for this can test several line structures, say 500, 1000, 1500 and 2000 lines, at little expense, so that this element of the specification is realistic. If not specified correctly, this could make an otherwise good computed display unrealistic. The interaction of computer storage capacity, frame rates, etc., is directly related to the number of picture elements. The detail of the scene, storage, and the complexity of slant range computation to control appearance, contrast, etc., of each object will have a large bearing on the size of the computer. Computer capacity should not be a limitation. Film tests will validate this.

Another example of the use of the computer-graphics film process used as a low-cost means of establishing the final specifications is that of allowable contrast and brightness variations. This can be controlled to a higher degree in filming (exposures, film speed, processing, and printing) than in a TV display using

a cathode-ray tube. The extent of the projected light intensity is important and can be readily varied in a film projector for establishing the most realistic average light levels in CAT II and CAT III conditions. Contrast and brightness ratios of the objects that vary in distance and thus in these characteristics can be portrayed on film for study. The sharpness of the images can be varied with film preparation just as in the case of the test film that presents different line structures.

This initial step with film has many advantages before launching into what is admittedly a costly and sophisticated, real-time computer graphics project. The computer-plotted film strips can in themselves be used to acquaint pilots with typical CAT II and III low visibility conditions by projecting them in a spherical screen with the proper eye location. This should tell the designer of the real-time computer generated display (of the outside, real world) much about the potential subject reactions to specific cues. Some cues that may be expensive to include in the simulator specifications may or may not be significant. The film strips can include cases of visual breakouts with the various dispersions of pilot errors, localizer errors, glide path errors, etc., so that the limits of the ultimate simulator can be tested, assuring realism but at minimum cost.

For example, a large costly fog chamber has been built that has proven most valuable in a series of tests with limited objectives. One serious limitation is that the pilot views the scene in an 800-foot-long "fog" chamber while moving on a track toward a scale-size runway that always places the subject on the runway centerline, at a perfect aiming point, with correct attitude; each condition is thus far from realistic.

The modifications of the fog chamber to include realistic lateral and vertical maneuvering, etc., is now considered an extensive project that might have been included for much less in the initial design. The Boeing Company and others have made such films for some years in the analysis of new aircraft, Navy carrier landings,

and in studying operational problems, so that several sources of low-cost film preparation under the controlled conditions herein suggested should be available.

G. CONCLUSIONS

From these film studies of the eventual scenes that will be generated in real-time and indicating the full dynamics of variable flight path and variable attitudes, a final set of specifications for industry bids can be generated. Such a national facility is badly needed, yet its importance, its cost, and the validity of the results that may modify some assumed principles of low-visibility landing must be fully and objectively established before such a project is committed. Some years may elapse and several millions of dollars may be spent, yet the entire development of a realistic, real-time, electronic low-visibility landing simulator will be less than the cost of a single landing accident that can undoubtedly be prevented in due time by the development of the simulator.

The significance of this statement can be measured by the statement of a British investigating team that stated in a report entitled: "A Flight Study of the Sidestep Manoeuvre During Landing". ". . . even the smallest correction from displacements of 75-100 feet, will need about ten seconds to complete, even if very rapid rates of roll are available." It should be noted that this is based on tests of around 1956 using aircraft in operation at that time--mostly propeller types much smaller than today's large, sluggish aircraft such as the 707, DC-8 jets and the forthcoming 747 and C-5A aircraft. A typical result of this British test (if confirmed with the very-low-visibility simulator outlined, could be devastating to existing CAT II plans) is--"Pilots stated however that they unvariably wished to complete the lateral correction before starting the landing flare." "Some sample measurements, on the larger transport aircraft tested, showed that the flare was generally started at a height of about 50 feet--so that the time

actually available for assessing the aircraft's position, and the time for making the lateral correction, would be about 25 seconds...." This is just the type of occurrence that needs full validation today for the large jet transport. If reconfirmed, this could cause modification to many current CAT II and III plans that may cost over 100 million dollars to achieve, calling for revision of ICAO ILS standards, AC 120-20, etc. Such a major national undertaking will eventually be necessary before any realistic and safe reductions in visibility are committed.

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APPENDIX

SSR "LISTEN-IN" FEATURE FOR PROXIMITY WARNING

A truly low-cost SSR (beacon) transponder can be developed that operates in a narrow channel on the edge of the SSR band, or in a cleared DMET channel (one of 126) adjacent to SSR. This transponder can serve general aviation within the National Airspace System with almost full compatibility.

Basically, all low-cost general aviation aircraft flying in airspace of any given traffic density would carry the low-cost transponder (under 500 dollars),presumably just as they now are required to carry VHF communication equipment. The rewards to the general aviation pilot will be equivalent if not greater than those derived from the VHF communications. Once all aircraft carry this unit, it is possible for a given aircraft to determine generally who is around him and how far away they are.

As the ground (rotating-beam) interrogator signal is received aboard the aircraft by the transponder receiver, the signal is decoded and used to trigger the transmitter part of the aircraft beacon (or transponder) unit. This reply is then received by the ground and is used in processing after some clean-up such as side-lobe suppression, de-fruiting, etc. However, if all aircraft had a means of "listening-in" at that specific instant of time when their own interrogation by the ground-originated signal takes place, measurements of the proximity of other SSR-cooperating aircraft are possible.

Assume a period just before and after the ground rotating beam interrogates the subject aircraft. This same beam also interrogates other aircraft near the same azimuth (as the subject aircraft). The proximity in angle and range of other aircraft, as determined by the ground station interrogations, can be available electrically in each cooperating aircraft by simply monitoring the reply channel. A so-called "listen-in" function can be used to listen to the synchronized replies of nearby aircraft. The time of reception of the ground interrogate pulse pail is a direct measure of the distance to the ground station. If a synchronized reply is heard on

a "listen-in" channel that is timed before or after the instant of interrogation of the subject aircraft, it is possible to determine the range of a nearby aircraft relative to the subject aircraft. This is useful for collision avoidance or for proximity warning.*

One simple way to do this is to use a gated crystal video receiver tuned to the reply channel. Since only the nearby aircraft, that would be a threat, are of concern to the subject aircraft, short transmission paths exist. Low sensitivity receivers are acceptable since the signals will be relatively strong (0-4 miles).

Thus, a simple output of a range gate that could be tapped to provide repetitive pulse signals that precede or follow the subject aircraft's own response by, say, 10 to 20 microseconds (up to about 4 miles) on either side of the subject aircraft's position would be indicated to the pilot. Fortunately, the time between transponder reception and transmission of a pulse is short and is standardized by being fixed at only 3 microseconds. A "dead-time" for transmitter recovery of 125 microseconds follows the transponder reply, so that the subject aircraft could now use its own receiver on a "listen-in" mode by simply switching local oscillators (after transmitting the reply sequence) for about 100 microseconds. This interception of adjacent signals could indicate the general direction of another aircraft (an intruder) near the subject aircraft; also, by noting the number of actual pulses in the reply (often about 20 to 30 for a given beamwidth), the location of the other aircraft relative to the scanning, interrogating beam would also be evident.**

If, for example, a beam of 3 degrees width is used and 31 pulses represent its width at a given rotation speed, the center of the beam is the 16th pulse (15 pulses on either side of a beam-split). If the subject aircraft now compares its 16th (or beam center) pulse with the center pulse of another adjacent

---

* Aircraft at approximately the same distance reply at approximately the same time; the difference in time between replies is equivalent to aircraft spacing when using the "listen-in" feature proposed.

** Even normal or intentional jitter (slight variation in pulse spacing) is acceptable on an average basis of, say, 30 pulses, since the norm would be a relative difference between the intruder and subject aircraft, not an absolute time difference
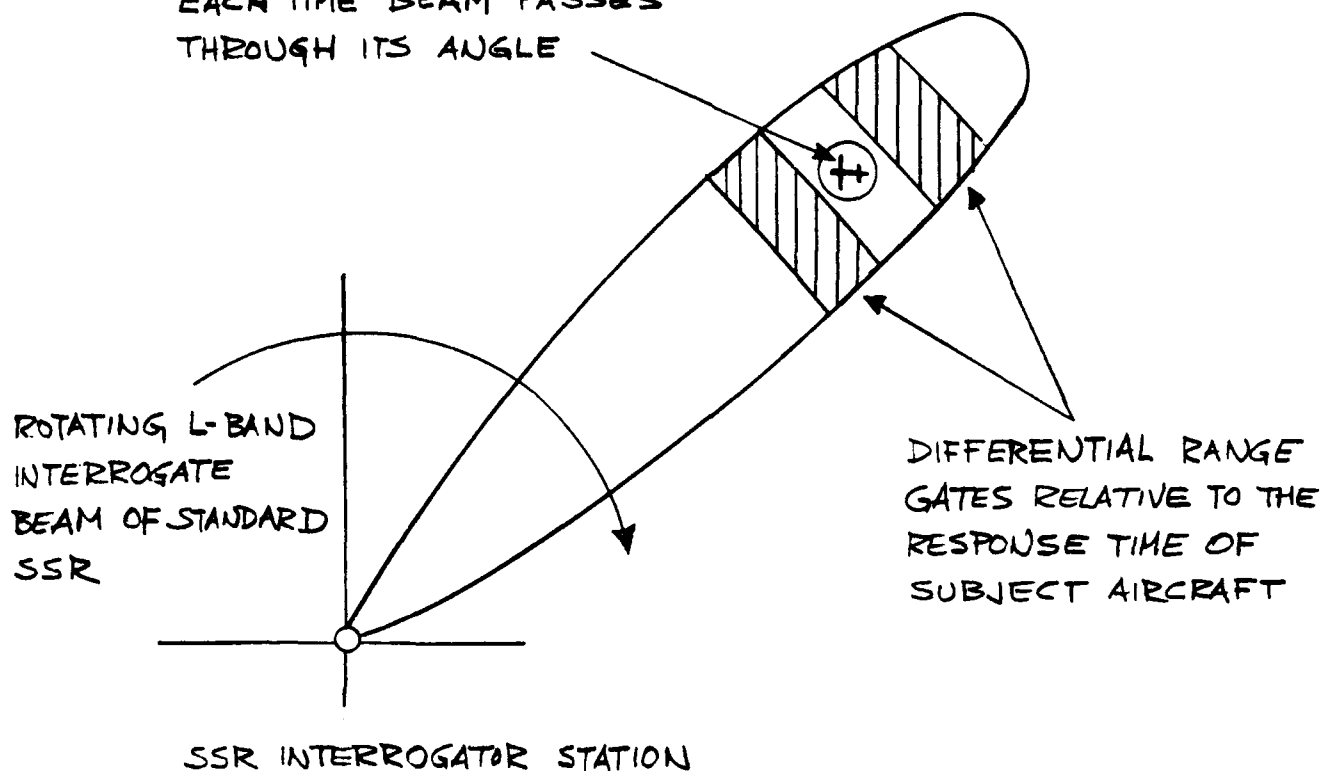
aircraft's transmission, it is evident that a leading or lagging time measure is available. This, in turn, implies that the intruding aircraft is on one side or the other of the subject aircraft relative to the interrogating beam. Since all interrogate beams can rotate in one direction at known speeds, this would provide an indication to the pilot of the other aircraft's approximate position (this is illustrated in Figures 29 and 30). The beamwidth tends to narrow in degrees of effective interrogation because of the propagation loss with range. There is thus a tendency for generating a more "rectangular"beam signal (as received in the aircraft) than an angular beam. The total number of pulses may vary for a given range, but the beam center is still always the middle of the pulse group heard from the adjacent aircraft (see Figure 31).

For example, at 20 miles from the interrogator, a 3-degree beam is about 1 mile wide at the 3-db points and about 6 degrees wide at the 8 to 10 db points, a level that will probably interrogate (even with side-lobe suppression). Thus, another aircraft within 2 miles on either side, would be heard by "listen-in" in this manner.

Another scheme is to use a simple timing circuit representing the rotation period of the beam, but since ARSR and ASR radars rotate at different speeds, this might complicate matters. Each, however, has a distinctive PRF and rotational speed that could be simply identified. The timing circuit would permit examination of other replies by the "listen-in" SSR technique at greater distances than those represented by the beamwidth. Even if a jittered pulse repetition rate is used, this can be ignored, because it is the reception of pulses always relative to the aircraft's own timing that is significant, and the jitter over 30 pulses follows an average relative delay (Figure 32).
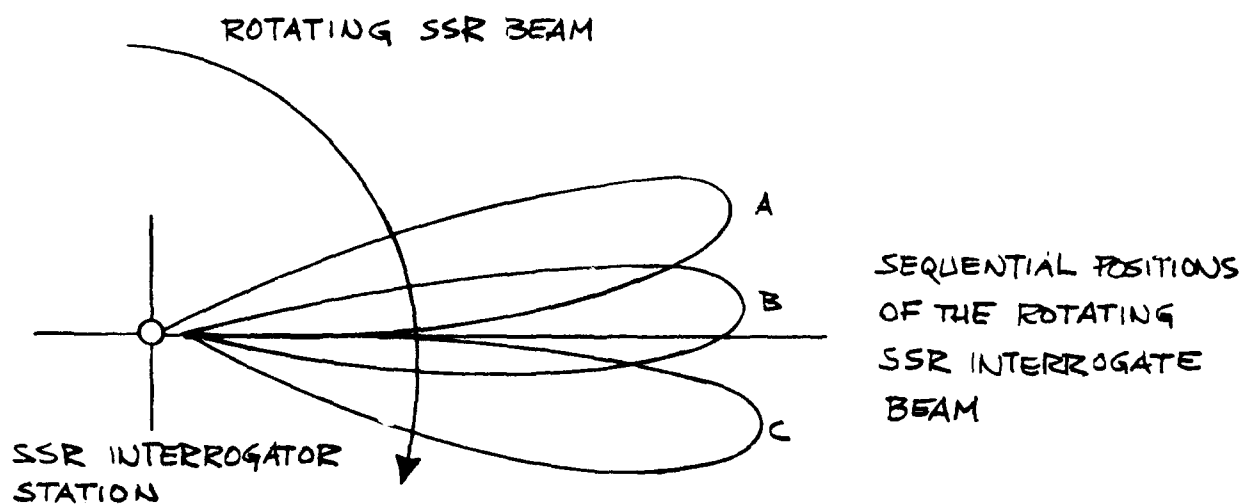
In summary, a simple "listen-in" feature added to the low-cost SSR general aviation transponder could provide a desirable proximity warning signal for all general aviation aircraft. Others

SUBJECT AIRCRAFT RECEIVES
20-30 INTERROGATE PULSES
EACH TIME BEAM PASSES
THROUGH ITS ANGLE

ROTATING L-BAND
INTERROGATE
BEAM OF STANDARD
SSR

DIFFERENTIAL RANGE
GATES RELATIVE TO THE
RESPONSE TIME OF
SUBJECT AIRCRAFT

SSR INTERROGATOR STATION

SSR PROXIMITY SIGNAL

FIGURE 29

ROTATING SSR BEAM

SEQUENTIAL POSITIONS
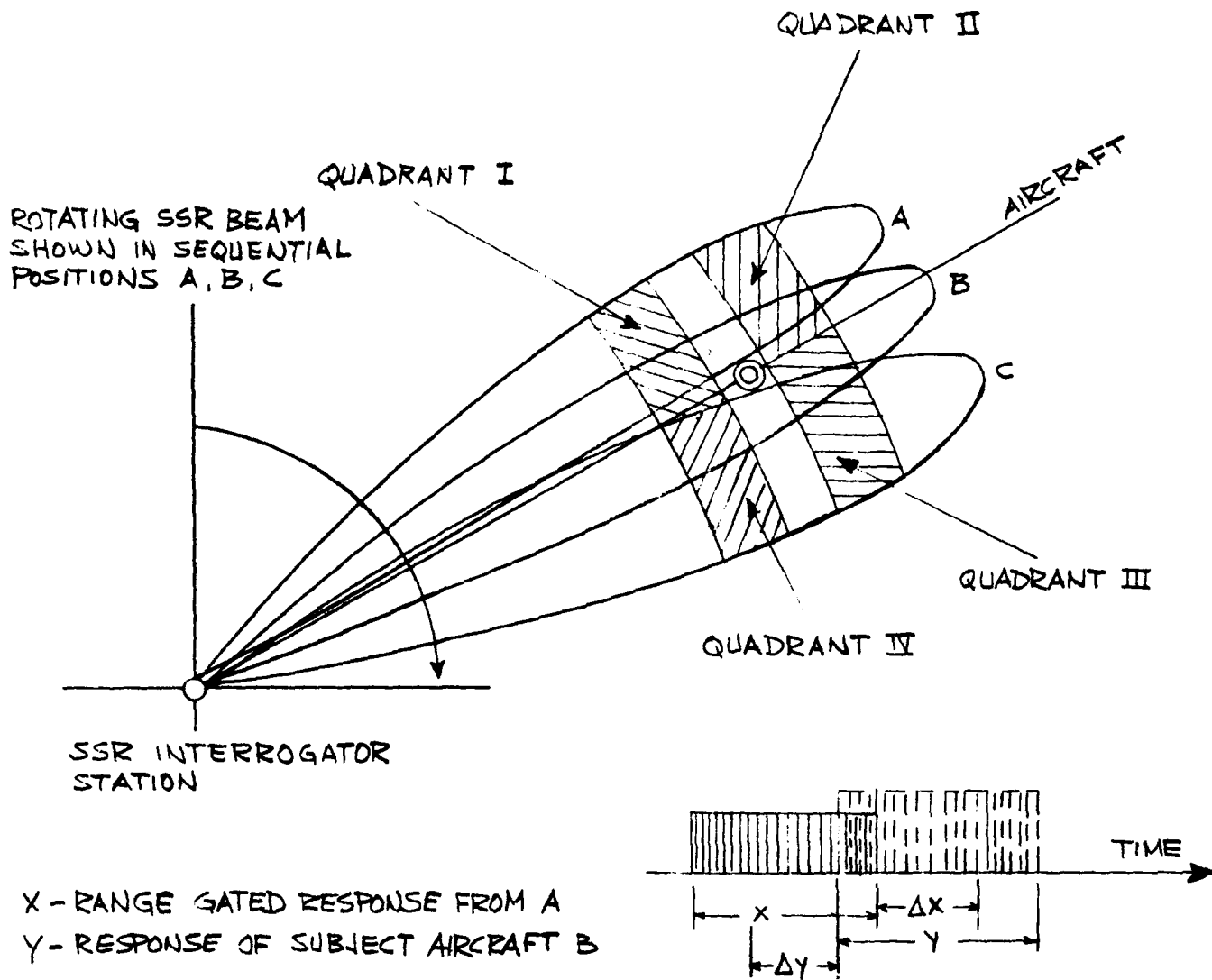OF THE ROTATING
SSR INTERROGATE
BEAM

A

B

C

SSR INTERROGATOR
STATION

Aircraft in Position B will hear replies
from any aircraft in position A or C
that is within range gate illustrated in
Figure 29.

SSR PROXIMITY SIGNAL SHOWING SEQUENTIAL POSITIONS
OF ROTATING SSR INTERROGATE BEAM

FIGURE 30

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QUADRANT II

QUADRANT I

AIRCRAFT

A

B

C

ROTATING SSR BEAM
SHOWN IN SEQUENTIAL
POSITIONS A, B, C

QUADRANT III

QUADRANT IV

SSR INTERROGATOR
STATION

TIME

X

ΔX

Y

ΔY

X - RANGE GATED RESPONSE FROM A
Y - RESPONSE OF SUBJECT AIRCRAFT B

SSR PROXIMITY WARNING SIGNAL

FIGURE 31

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RECEIVED SIGNAL IN AIR

THRESHOLD   NOSE OF BEAM

AIRBORNE REPLY

5

TRANSMIT   "LISTEN-IN"

BEAMWIDTH

TR SW — TRANS — NORMAL

M — IF AMPL — DECODE

LO

① ②

RING'G OSC — DISABLE

LOCAL P. GEN — COUNT 5

RANGE GATE

SWITCH TO ① FOR NORMAL

SWITCH TO ② FOR "LISTEN-IN"

"ALT LISTEN IN"

BEAM POS DIFF   RANGE DIFF

+ − + −

SIMPLE 4 LIGHT COCKPIT DISPLAY
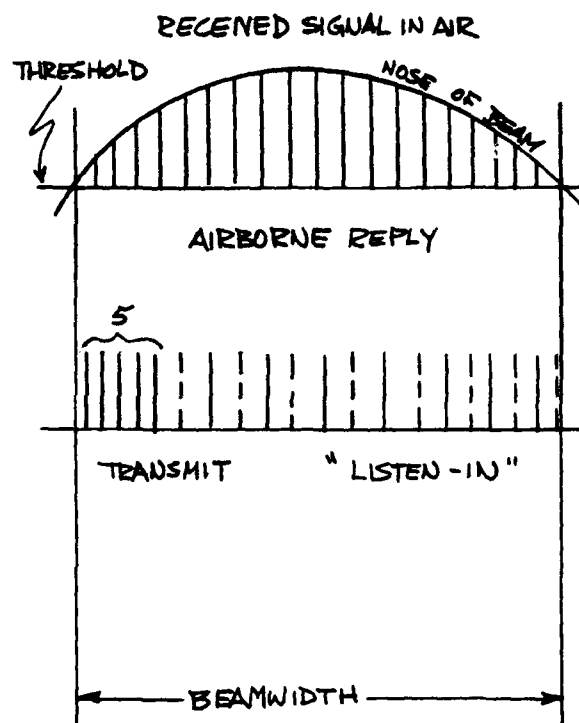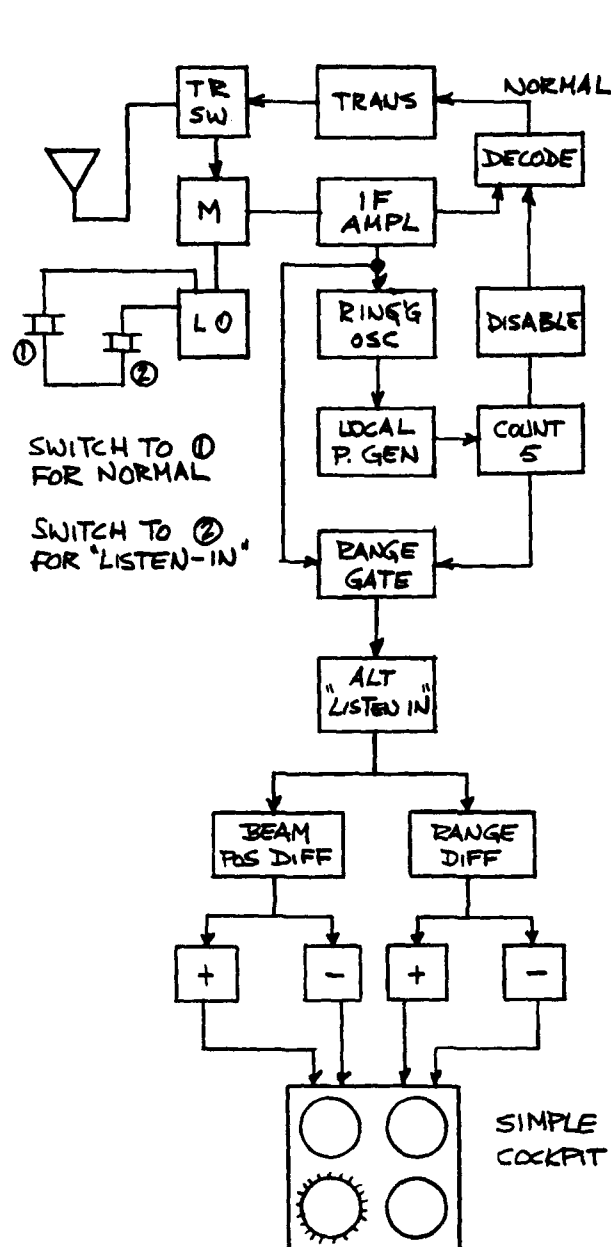
After count of 5 received interrogate pulses from ground SSR, alternate reply and listen-in functions occur. Local ringing oscillator permits synchronized listen-in by switching local oscillator and disabling trans- mitter. During listen-in pulse periods differential timing (range difference) and differential beam position signals provide approximate quadrant of any other replying aircraft which by virtue of range gate limits and beamwidth limits may be a hazard. Proximity is shown by a single light or possibly 4 quadrant lights.

SSR PROXIMITY WARNING FUNCTION ADDED TO LOW—COST
GENERAL AVIATION OR STANDARD ATC TRANSPONDER

FIGURE 32

using the same function would benefit perhaps even more. The signal could be range- and angle-gated to include up to about 2 to 4 miles in all directions for a warning. It could give a simple quadrant type indication to the pilot of the direction of the adjacent aircraft. Often these aircraft may be at other altitudes,which can be quickly determined through VHF communications between pilots or with ATC. Automatic altitude transmission by military and air carrier aircraft will greatly aid.

If the other aircraft is a hazard, this can be quickly established by simply maneuvering (something possible in a slow, single-engine general aviation aircraft, which differs considerably from the "jet-to-jet" collision avoidance problem) to a direction that will take him away from the dangerous quadrant. Since the quadrants are all referenced to the aircraft itself in the simplified "listen-in" system, the general direction of the potential intruder is known by the electrical signals (lead or lag pulse and before or after beam center). The flight path relative to the ground station establishes these coordinates in both aircraft.

Voice communication is still the most flexible and immediate means for solving such conflicts. It fulfills almost all needs of air-to-air warning between pilots in a cooperative system such as that exemplified by the SSR system. It is expected that at least all pilots in a given airspace, even in VFR, will use VHF radio and, if it fails, the failed aircraft is declared an "emergency" so that this means (VHF-communication) can be used to resolve the geometrics of the potential conflict.

Most proposed or existing CAS systems are so complicated they cannot be added to general aviation aircraft. The computation of the "escape" maneuver for both aircraft is still under theoretical study. It is apparently so complicated that an automatically computed "escape" path is needed. For general aviation such complexity will not be economically feasible whereas, a simple concept is.

The added value of radar tracking, ATC identification,

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emergency warning to the ground, and now the potential of a simpli-
fied, yet effective proximity warning signal—all services derived
from a single low-cost SSR transponder--should appeal to both the
general aviation pilot who has limited financial means as well as
the airlines and government authorities (that regulate both).
Resolving what appears to be a major impasse between these three
parties in the near future is essential. Without technical means
of low-cost, three-way cooperation, this impasse will soon deepen.